Opportunities for fine coal utilisation

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Abstract

Coal is prepared to meet end-user requirements such as limits on the proportion of fine coal and ash forming minerals in the product. Preparation methods leave residues of fine material which can have a wide range of compositions from a good coal product to very high ash, surface moisture and sulphur contents. Regardless of composition, at the time of generation of these residues no market for them existed and so large amounts (estimated as about 58 Gt) have been deposited around the world in heaps or in slurry impoundments. Changes to the value of coal and developments in coal preparation and utilisation technologies have enabled increasing amounts of these materials to be recovered and used. The report provides an overview of the resource and opportunities for utilisation.

Abbreviations

AC	alternating current
AMIS	Canadian Abandoned Mines Information System
AMLIS	Abandoned Mine Land Inventory System
ar	as received
BFBC	bubbling fluidised bed combustion
BHEC	Beijing Huaya Engineering Co
BOM	build, own, maintain
BSI	British Standards Institute
CCRI	China Coal Research Institute
CFBC	circulating fluidised bed combustion
CIMFR	Central Institute of Mining and Fuel Research (formerly Central Fuel Research Institute, CFRI)
CIL	Coal India Limited
CLM	coal liquid mixture
CMM	coal mine methane
CPP	coal preparation plant
CSD	coal slurry deposits
CSIRO	Commonwealth Science and Industry Research Organisation
CV	calorific value
CWM	coal water mixtures
db	dry basis
DC	direct current
DMC	dense medium cyclones
DMS	dense medium separator
ECSC	European Coal and Steel Community
EJ	exajoules (10^{18} J)
EPCAMR	Eastern PA Coalition for Abandoned Mine Reclamation
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
FBC	fludised bed combustion
GESI	Global Environmental Solutions Inc
GOB	garbage of bituminous
GOI	Government of India
GT	gas turbine
HCGT	hybrid coal gas turbine
HLB	hydrophile-lipophile balance
HRSG	heat recovery steam generator
ICE	internal combustion engine
ICOLD	International Commission on Large Dams
IDGCC	integrated drying and gasification combined cycle
IDNR	Illinois Department of Natural Resources
IGCC	integrated gasification combined cycle
IPGCC	integrated plasma gasification combined cycle
LHV	lower heating value
LRC	Legislative Research Commission (Kentucky)
maf	moisture and ash free
MDC	Mineral Development Corporation
MSHA	Mine Safety and Health Administration of the US Department of Labor
MSW	municipal solid waste
MWD	Mining Waste Directive

NAOMI	National Orphaned/Abandoned Mines Initiative
NCB	National Coal Board, UK
NSW	New South Wales, Australia
OSM	Office of Surface Mining – Reclamation and Enforcement
PC	pulverised coal
PCFBC	pressurised circulating fluidised bed combustion
PADEP	Pennsylvania Department of Environmental Protection
PGVA	plasma gasification vitrification of ash
POC	proof of concept
PRB	Powder River Basin
QLD	Queensland, Australia
RCRA	Resource Conservation and Recovery Act
RDF	refuse derived fuel
RF	radio frequency
ROM	run-of-mine
SCLCI	Swiss Centre for Life Cycle Inventories
SMCRA	Surface Mining Control and Reclamation Act
SNCR	selective non-catalytic reduction
US DOE	US Department of Energy
US EPA	US Environment Protection Agency
VAM	ventillation air methane
WPCAMR	Western Pennsylvania Coalition for Abandoned Mine Reclamation

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1 Introduction

A considerable proportion of material extracted during coal mining is rejected. This includes material that is largely a by-product of coal processing, having significant energy content and small particle sizes including substantial amounts below 0.15 mm. Such fine coal is difficult to handle and poses significant technological challenges for storage and utilisation. Storage requires measures to contain the resource cost effectively whilst avoiding adverse impacts on people and the environment. The options for utilisation are constrained by the moisture generally associated with fine coal and wide variations in ash content. In addition fine coal is sometimes placed together with other materials and this also affects the scope for utilisation. Historically, blending, briquetting and drying have been adopted to facilitate use of fine coal.

This report considers the scale of the resource that these residues represent at global and national levels. This includes both existing stocks and current generation rates. The approaches that have been adopted concerning the storage of these materials, together with the associated health, safety, environmental and economic impacts, are outlined.

Opportunities for utilisation of these materials are reviewed and include coal preparation developments for fine coal recovery, adaptation of existing technologies to accept recovered coal production residues, and emerging technologies and new strategies for extracting value thus turning the problem into an opportunity.

2 Context

2.1 Terminology

Standard definitions of coal preparation terms are provided in ISO 1213-1:1993 (BSI, 1994). However, there are numerous terms relating to coal preparation residues in the literature. Different terms are used for similar features in different countries, and even in different districts of the same country. In different locations the same term may have different meanings and there is no comprehensive and unambiguous set of terms to cover the subject matter of this report. So the terms used are identified and defined for the context of this report.

It is common in the literature for the term ‘coal’ to refer to the whole material including both the organic and inorganic material. There is no defined point at which the description of a material moves from coal to rock, with materials of 80% ash sometimes referred to as coal. In the context of this report this may lead to some ambiguity where material referred to as coal may have very high ash content. Where required for clarity the following differentiation is made. Where the energy containing carbonaceous fraction is dealt with specifically the term ‘organic coal’ will be used and where the ash forming mineral component is in question the term ‘inorganic matter’.

All the material that is extracted but which does not report as product will be termed ‘coal production residue’ and falls into two main categories:

- mining spoil (from shafts and roadways in underground mines or overburden from opencast mines);
- material rejected by coal preparation processes, which may be either wet or dry depending on the processes that produced it.

This second group is referred to here as ‘coal preparation residues’ and is broadly divided into two size-based categories:

- coarse coal preparation residue;
- fine coal preparation residue, often defined as –5 mm, however there are instances where the stated top size is 6, 8, 10 and even 20 mm and many occasions where no definition is given.

The term ‘ultrafine’ is used in some literature. It does not always refer to separate process streams but is sometimes a subset of the fine residues. This is sub mm-sized material but the defined top size varies (Zhang, 2007 –50 µm; Battersby and others, 2003–150 µm – though both suggest that ultrafines typically represent about 10% of coal).

Whilst this size-based differentiation is convenient, many preparation processes depend on physical properties such as density or surface properties to achieve separation, rather than particle dimensions. Coal preparation residues can also be considered as:

- dry screened fines resulting directly from coal cutting and generally high in organic coal;
- wet washery rejects which have a wide range of compositions but generally high in inorganic material and moisture.

This does not give the complete picture as some washery processes can be undertaken with dry separation processes, an approach prompted by the limited availability or high cost of water in some places.

Interest in dealing with the issues associated with residues from mining has been rising and a recent new standard for geospatial recording of coal production residues (ASTM, 2010) provides descriptions of some relevant key features:

- Excess Spoil Structures – created when the total spoil produced during mining exceeds the volume of material that can be utilised for reclamation.

- Coal Preparation Plants – facilities where coal is separated from non-combustible materials, and potentially crushed, resized, and blended with other grades of coal.
- Refuse – by-products of coal processing, generally categorised as either coarse or fine. Fine coal refuse often is handled as a slurry containing a blend of water, fine coal, silt, sand, and clay particles.
- Impounding Refuse Structures – create a holding area for slurry that allows solids to settle out and water to be recovered. Cross-valley and dyked impoundments utilise an embankment, often constructed of coarse coal refuse, which forms a basin for slurry retention. Incised impoundments dispose of slurry in an excavated area below the natural surface and do not utilise a significant embankment for slurry retention.
- Non-Impounding Refuse Structures – may contain slurry that has been dewatered and stabilised prior to disposal. Non-impounding structures also may utilise slurry cells to dispose of fine refuse.

The materials covered by this report are often referred to in such terms as reject, discard, refuse or waste. The US EPA (2011a) suggested that definitions of coal refuse are based on the material having a minimum calorific content. However, as preparation and utilisation technology develops, the level at which the materials can be considered as a resource must necessarily change.

The focus of this report is on the potential for utilisation of these materials and in general the term 'residue' is used.

2.2 Coal preparation development – causes and effects

All methods of coal mining result in extraction of inorganic matter (for example dirt, clay, rock) that is at best unwanted and at worst a source of nuisance or hazard. They also generate finely divided coal which may not be acceptable to some customers. Removal is relatively easily achieved by screening but removal of the inorganic material has presented greater challenges.

Where the intermixing of the two components is negligible the separation is relatively easy. The more intimately associated they are the more difficult the separation process becomes and a greater degree of breakdown is required to liberate the components. Modern processes use particle size, density and surface properties to effect separation.

Coal preparation has received much attention and assessments of the range and capabilities of the techniques and technologies applied are available (Budge and others, 2000; Couch, 2000, 2002; Nunes, 2009). It is not the purpose of this report to provide a detailed description of coal cleaning technologies and operations in general. However, the progression of coal preparation provides the background to the distribution and characteristics of current stocks of coal preparation residues. Provision of a definitive chronology of coal processing developments is not practical, as the picture is complex and location-specific, but it is discussed briefly and in general terms here.

Coal mining has a long history but significant processing after extraction is a much more recent feature. Although the cleaning techniques available have improved with time they cannot provide a complete separation. So, unless coal is used as run-of-mine (ROM), as extracted, some organic coal material is generally discarded.

Coal processing has developed in response to two main drivers; product quality demands from users and environmental constraints from legislators and regulators.

The first consumer requirement to be addressed was the size distribution of the coal material. In industrialised societies in the 19th and early 20th centuries the main requirement was for large lump coal. An early approach was to remove only large (>300 to 500 mm) pieces of coal from the mine with all finer material compacted into the mine floor or dumped in abandoned areas of the mine. This was practical and did not lead to high proportions of lost coal. It resulted in very little inter-seam dirt being taken, and relatively little of the coal broken down into fine particles. The disposal problem was largely limited to the rock and dirt removed during mine development (sinking of shafts, boring of tunnels, etc).

Mechanisation of the coal cutting process reduced the ability to differentiate between coal seams and inter-seam dirt, or roof or floor material above and below the seam. This led to more inorganic matter being extracted. Mechanical cutting also generated much higher levels of fine material and, when coupled with mechanised removal from the coal face (continuous miners), the level of fine material exiting mines increased considerably. As fines generation increased, screening became established practice with fine residues, of mainly good quality coal, dumped on the surface.

The metallurgical industries have particular requirements and coal for these markets were the first, and for many years only, coals to undergo significant coal cleaning.

The requirements for thermal coals tended to be less demanding. For example combustion devices with grates have minimum ash requirements to protect them from the heat. So, thermal coal preparation was limited to crushing to size and screening to remove rocks, debris and fine coal. Pulverised coal (PC) fired boilers were typically designed for coal producing about 20% ash although designs are tailored to the properties of the anticipated supply fuel. So, where indigenous coal quality is low and washability is poor, boilers have been designed for coals of much higher ash content. For example in India PC fired boilers were usually designed for coal of 40% ash.

The introduction of legal requirements aimed at reducing sulphur emissions acted as a driver for coal producers to wash coals in order to remove sulphur-bearing minerals such as pyrite. So where such legislation came into force there were significant increases in the amounts of coal washed and so preparation residues produced.

In future, legislation on emission of other species may lead to demand for their reduction in coal supplies. Mercury is one such species, and Mak and others (2008) undertook laboratory-scale studies on the potential for air dense medium fluidised bed separation to reject mercury with inorganic mineral matter. In cases where the mercury is strongly associated with the inorganic minerals the technique showed promise for pre-combustion mercury control. Such demands will again change the nature of the residues deposited from preparation plants and present considerable new challenges in their disposal or utilisation.

Coal preparation technologies have developed in response to demands. However, the state of industrial/economic development in different countries, and the infinitely variable nature of coal, have led to wide variations in the techniques used and the amounts and properties of residues produced. Techniques superseded in some places (such as reliance on hand picking to separate rocks from coal) continue to be used in others. Techniques which are successful with some coals are abandoned elsewhere as ineffective. For example the use of spiral concentrators was discontinued in Vietnamese coal preparation plants as they were found to be inefficient in that context (Bach and others, 2006).

Local commercial practices have influenced the rate of deployment of coal cleaning. Coal cleaning is disincentivised by systems where income is based on the amount of material delivered, rather than the product quality. If delivered energy content is the determinant, savings resulting from reducing the amounts of valueless inorganic material transported long distances can make coal cleaning worthwhile. To address this issue and to minimise fly ash generation from June 2002, the Indian Ministry of Environment & Forests limited the ash content of coals and coal blends to 34%, when supplied to any thermal power plant located (GOI, 1997, 1998; Administrative Staff College of India, 2010):

- >1000 km from the pit-head;
- in urban, 'sensitive' or critically polluted areas, irrespective of their distance from pit-head.

In 2000 this applied to around 85.5 Mt of coal for 39 power plants (GOI, nd). In consequence many new washeries have been built or are planned in India, thus increasing the amounts of residues being generated. Power plants using fluidised bed combustion (FBC) or integrated gasification combined cycle (IGCC) technologies and pit-head power plants were exempted from using beneficiated coal irrespective of their locations.

Coals produced for export markets are often cleaned when those for indigenous use are not. In some circumstances residues from export coal preparation are supplied as fuel to local users (Boyd, 2009). The amount of coal preparation residues generated has been influenced by the development of the world coal trade.

2.3 Coal preparation residues – production and storage

The properties and amounts of the materials discarded to store change depending on mining and preparation technology and practices which can change significantly over the lifetime of a mine, preparation plant or a particular store (heap or impoundment).

Ghosh (2007) estimated that there were more than 2500 coal preparation plants in operation in the world, mostly distributed between the major coal-producing countries (Table 1), and that more than a third of world coal production was being beneficiated.

Table 1 Coal preparation capacities in various countries (Ghosh, 2007)

Country	Year	Coal production, Mt/y	Number of washeries	Capacity, Mt/y
China	2005	2226	2000	800
USA	2006	1100	265	986
India	2006	432	53	134
Australia	2005	397	70	NA
South Africa	2004	307	53 + 5 closed‡	162‡
Russia	2005	300	87*	95
Poland§	2004	160	50	91
Canada	2003	62	13†	35

* Includes 42 CPPs, 28 concentrators and 17 mechanised sizing units
† Nunes (2009),
‡ de Koort (2000),
§ Blaschke and Gawlik (2004)

The level of cleaning affects the amount and quality of material discarded. Various rankings for the level of coal cleaning have been developed, such as one developed for EPRI by Gibbs and Hill Inc (1978) that defined six levels:

- Level 0: Absence of preparation indicates that the coal is shipped as mined.
- Level 1: Breaking for top size control only, with limited, if any, removal of coarse refuse and trash.
- Level 2: Coarse beneficiation through washing of >3/8" (~9 mm) material only: 3/8" (~9 mm) x 0 fraction remains dry and is recombined with the clean coal prior to shipment.
- Level 3: Deliberate beneficiation through washing of all >28 mesh (0.6 mm) material; 28 mesh (0.6 mm) x 0 material, depending on its quality, is either dewatered and shipped with clean coal or discarded with the refuse.
- Level 4: Elaborate beneficiation through washing of all size fractions, including 28 mesh x 0. Thermal drying of 1/4" (~6.4 mm) x 0 sizes is generally required to limit moisture content.
- Level 5: Full beneficiation implies the most rigorous coal beneficiation.

This ranking approach was subsequently used to develop a coal cleaning module for a model for estimating solid waste from fossil fuel technologies (Crowther and others, 1980).

Preferred coal preparation technologies in major coal-producing countries were summarised by Ghosh (2007) (*see* Table 2).

Modern preparation plants reject much lower fractions of organic coal than those based on older technologies. However, there are still many cases where significant amounts of organic coal are rejected from preparation plants and stored.

New coal mining developments are much more likely to be accompanied by a mechanism for dealing with the preparation residues. In China numerous minemouth power plants fuelled by 'waste coal' have been built. The IEA CCC CoalPower database lists 64 units, mainly CFBC, coming into operation since 2004, with a rated capacity of 8.48 GW. A further 11 units are either planned or under construction that would add a further 1.53 GW of capacity.

The European extractive industries, including the energy extractive sector, employ a range of similar waste management methods (DHI Water Environment Health and others, 2007):
- waste-rock and tailings are to a large extent backfilled where possible;
- waste-rock and tailings are used as building material where suitable and possible;
- coarse waste-rock and coarse tailings are managed on heaps or in old excavation voids, if not backfilled into the operating mine or used as construction materials on- or off-site;
- tailings from dry processing are managed on heaps or in old excavation voids, if not backfilled into the operating mine or used as construction materials on- or off-site;
- tailings from wet processing are managed in tailings ponds or in old excavation voids, if not backfilled into the operating mine or used as construction materials on- or off-site.

These descriptions are broadly applicable to disposal of coal production residues globally. However, storage and site reclamation practices do change with time and affect the recoverability of any residual organic coal material.

The use of impoundments to store coal tailings slurry has risks associated with it. Alternatives that avoid or mitigate their use have been developed including:
- paste and thickened tailings – reducing water, reagent, energy, storage space demand and risk of store failure (Dunn, 2004);
- slurry cells – small, low risk impoundments;
- Co-disposal of coarse and fine washery residues or with other materials such as power plant fly ash – fines occupy voids between coarse particles, thus improving storage utilisation and the engineering properties of the material (Day and Riley, 2004; Dunn, 2004);
- underground slurry injection – pre-preparation may be required to provide the required properties for example a pumpable stable paste may be required to enable storage in such areas as abandoned roadways and voids behind coal faces (both collapsed and not collapsed (Astle, 1993)) – any residual organic material is lost with this method;
- injection of slurry into membrane tubes – this has proved successful in at least one application (TenCate, 2009).

MSHA (2009) provides a comprehensive design manual for the construction of impoundments for storage of coal preparation slurries as well as discussion of the alternative technologies available.

The storage strategy adopted impacts on the potential for subsequent recovery of organic coal from the residues. Determination of the scope for recovery of organic coal from stored residues may require detailed records of past activities and extensive surveying of the material stored.

Concerns over the impacts of disposal of mining wastes in general have prompted considerable

Table 2 Preferred coal preparation technologies for major coal producing countries (Ghosh, 2007)

	Comminution	Coarse washing	Medium washing	Fine washing	Dewatering
Australia	Crush to 50/60 mm	Mainly by DMC (diameter1000 mm or more) Drums or baths in some plants Jigs at few plants.		Spiral + Jameson or microceltechnology Limited use of froth flotation for metallurgical coal	Coarse and medium size-vibrating or scroll type basket centrifuges Flotation products-vacuum filters and screen bowl centrifuges Tailings-high rate gravity thickener and belt press filter
China	Crush to 100/50 mm	Mainly jigs (60%) Dense medium separator (Drewboy, vertical lifting wheel separator)	2-product dense medium cyclones (diameter 660–1300 mm) 3-product dense medium cyclones (diameter 1000–1400 mm)	Mainly flotation Column flotation (for very fine coal)	Mainly high frequency screen Centrifuge (vertical & horizontal) Pressure filter Fast diaphragm filters Plate-and-frame filters (slime recovery)
USA		Dense medium vessel	Dense medium cyclones (diameter<1000 mm)	Water-only cyclone Spirals Combination of both froth flotation (very fine coal after desliming: 35–40 μm)	Coarse size fraction - basket type dryers Fine size fraction - screen bowl centrifuges - combination of vacuum filter and thermal dryers
Russia		Heavy media baths & cyclones Jigging Flotation High-angle separators (water-only cyclones) Spiral separators Pneumatics (for thermal brown coals)			High frequency screens Centrifuges (settling & filtering) Belt press filters Continuous disc filter (operating under pressure)
Canada		Dense medium vessel	Dense medium cyclones (diameter <1000 mm)	Water only cyclone Spirals Combination of both Froth flotation (very fine coal)	
South Africa	Crush to 80 mm	Mainly large diameter pump fed dense media cyclones Dense medium separator (Wemco Drum, Drewboy) Jigs at few plants.	Smaller diameter cyclones	Limited use of froth flotation Mainly spirals	
India	Crush to 100/75/50 mm	ROM jigs (moving screen jig) Coarse coal jigs Dense medium separator Barrel washer	Small coal jig Dense medium cyclones (diameter 600–1000 mm)	Flotation Spirals Water only cyclones	Vacuum filters High frequency screen Centrifuge Belt press filter

research and review activities which have led to the development of legislative requirements and regulatory structures (*see* Chapters 3 and 4).

2.4 Factors affecting quantification of resource

In addition to those associated with coal production various other factors also affect the amounts of organic coal present in a stock. In this section these factors are summarised. Section 5.1 discusses approaches to identifying and assessing stocks of coal preparation residues.

2.4.1 ROM coal properties

The composition of ROM coal can vary significantly even where a single seam is worked as the working coal face moves through bands of dirt, up or down a gradient and over significant distances. The situation is more complicated if several seams are being mined simultaneously and processed through the same coal preparation equipment.

2.4.2 Deposition effects and post-deposition changes

Slurries of fine particles suspended in water are pumped from preparation plants to impoundments. The deposits in coal slurry impoundments have three common features:

- the discharge point where the slurry enters the impoundment and away from which the liquid flows at velocities dependent on the flow rate;
- the fan shaped deposit (referred to as the 'beach' or 'delta') which results from the settlement of the suspended solids as the fluid velocity drops below the entrainment velocity, and which is highest adjacent to the discharge point, tapering down moving away from it;
- the settlement pond whence flows the liquid.

The settling properties of the various particles determine the distribution of organic coal in a delta. In general, denser particles are deposited close to the discharge point with the density of the deposited material decreasing as the distance increases. In impoundments material of different properties (coal fines, silt, and sand) are deposited in a predictable manner when the conditions (the discharge rate into the impoundment and the discharge point) are constant and the shape of the impoundment is known. The development of the delta (beach) within a tailings pond may be modelled with some degree of accuracy if the key parameters are known (Morris and Williams, 1996).

However the settlement patterns observed are not necessarily those predicted. One factor is that the material being discharged may change over time if developments in mining and preparation technologies are implemented.

At one site it was predicted that organic coal would settle away from the dam in a fan of sediment, and clay particles nearer to the dam, but regular monitoring found no such relationship in the sedimentation pattern (Kuzev, 1998). Even where sedimentation rates are as predicted the deposition patterns are unlikely to be uniform as channels may develop where high liquid velocities occur. Cobb and others (1979) concluded that: 'The physical features of the slurry deposit within the impoundment constantly change shape and position, responding to variation in the slurry discharge load, to build-up of the deposit, to bulldozing for control of channel development, and to the position of the water line.'

After deposition further changes may occur. As coal cleaning technologies develop, residues previously deposited may be reprocessed to recover further coal. Where areas of stocks contained high concentrations of organic coal this may have been selectively re-mined and utilised and the overall composition of the stock may differ from that expected based on original records.

Heaps may be re-contoured during their life so that the position of material may be different from that expected based on site records. In some cases whole heaps may be moved.

2.5 Scale of the resource – a global estimate

In this section the potential amount of deposited coal preparation residue is considered at a global level. Where available, estimates of the amounts present in individual countries are presented in Chapter 6.

2.5.1 Quantity

Fines associated with ROM coal are typically in the range of 10% to 20%. An early form of coal preparation was simply to screen out this material. Often the term 'tailings' is used to refer to the finer material and particularly to that which results from wet separation processes.

Overall 20–50% of the material delivered to coal preparation plants may be rejected (Miller, 2005) and based on information relating to the mid-1990s, Couch (1998) estimated that ~600 Mt/y residues were produced from coal washeries in ten of the then top seventeen coal-producing countries.

The Swiss Centre for Life Cycle Inventories (SCLCI) (http://db.ecoinvent.org) uses a value of 1167 Mt/y for global tailings production from hard coal, a rate of about 19.5% when compared to the World Coal Association estimate for hard coal production in 2009 of 5990 Mt/y (http://www.worldcoal.org/resources/coal-statistics/). SCLCI also assigns rates of spoil production from coal mining and lignite mining as 22,240 Mt/y and 3900 Mt/y respectively.

Hubbert (1981) estimated that global coal production had amounted to around 7 Gt by 1860, and that by 1976 this had risen to around 158 Gt. Production of fine material prior to 1860 was limited as the extraction techniques were manual and any produced was left underground. Global coal production to date is estimated to be around 300 Gt with total stocks of fine residues of around 58 Gt, representing about 800 EJ.

The methodology for deriving these estimates is presented in Annex 1. This estimate is limited by the need to use some broad assumptions and thus has a high level of uncertainty. Available estimates for individual countries are presented in context in Chapter 6. Some countries with long histories of mining have large deposits of fine residues that have potential for recovery and utilisation. However, as the USA with the largest stock of fine coal preparation residues is estimated only to have around 4 Gt the global estimate presented should be considered as a potential maximum.

2.5.2 Quality

There are five main factors that determine the quality of recovered coal fines (Schimmoller and others, 1995):

1. parent coal characteristics;
2. mining technique;
3. preparation procedures;
4. efficiency of the preparation plant;
5. degree of oxidation.

These variables can change throughout the life of a coal preparation residue deposit. Leonard and Lawrence (1973) postulated a history for a typical anthracite culm bank over the period from 1917 to 1972 (a key year in the USA with changes to coal production practices having been implemented due

Table 3 History of a hypothetical US refuse pile (Leonard and Lawrence, 1973)

Year	Mining	Preparation	Reject	Store
1917	Not mechanised to any extent	Picking and screening	Handpicked rocks and screened undersize	Fine material (mainly organic coal) dumped with rocks. Fines tend to concentrate in interior of pile, rocks along edges.
1920	Greater selectivity in mining	Facility enlarged, more rigorous sorting and sizing	Handpicked rocks and screened undersize	Increase in amounts deposited
1923	Some mining machinery introduced, selectivity reduced		Rocks, fine coal and other dilutants	Increase in amounts deposited, more higher ash and sulphur material
1925		Concentrators added		Less fuel value, relatively higher in rock and ash than ever previously
1929		Rigorous preparation		Limited growth, relatively large amount of fines
1933	Additional mechanisation			Fluctuating tonnages of high ash/high fuel value material placed
1940			High ash, moderate sulphur material	Fuel rich areas re-mined
1945	More advanced equipment	More advanced equipment installed	High ash, high sulphur, moderate fuel value material	
1950	Additional mechanisation	Crushers added and process efficiency improved	High ash, high sulphur, very low fuel value material	
1969			High ash, high sulphur, low to moderate fuel value material	Much more material being deposited. Older sections re-mined to recover previously discarded fuel
1972		New more costly concentration technology installed	Medium ash, high sulphur, moderate fuel value material	Large amounts deposited but old areas of moderate ash, moderate sulphur and moderate fuel value material being re-mined

to the introduction of air pollution control legislation in 1970). Key events affecting operational practices and developments of the hypothetical site are identified and the impacts on the development of the store noted. This is summarised in Table 3.

Numerous analyses of the composition of recovered fines have been made. For the purpose of life cycle analysis of coal tailings Doka (2009) estimated a typical composition based on a survey of published information (*see* Table 4).

The uncertainty associated with the values for some elements is high with fewer than ten data points in some cases. For Sn, Sc, Tl and W no information was found though, in the case of W an estimate of 0.035 mg/kg was made.

For utilisation considerations energy and ash contents are key considerations. The compositions of coal preparation residues cover wide ranges for these parameters, with calorific values of 5 to 30 MJ/kg db and ash contents from 10% to 80% db.

Table 4 Estimated elemental composition coal tailings (solids) (Doka, 2009)

Element	Concentration, mg/kg
C (org)	124000
S	5562
N	42.66
P	689.6
Cl	445
F	1.86
Ag	0.00354
As	4.451
Ba	65.52
Cd	0.6397
Co	3.429
Cr	26.07
Cu	19.39
Hg	0.0486
Mn	72.54
Mo	1.335
Ni	16.29
Pb	18.38
Sb	0.1281
Se	0.7467
V	8.684
Zn	54.27
Be	0.5928
Sr	19.38
Ti	137.3
Si	239.1
Fe	6103
Ca	1101
Al	3130
K	1317
Mg	858.6
Na	685.5

3 Drivers

Many stores of coal production residues have existed over long periods, many decades in some cases. Others have been made more recently but regardless of their history it is unlikely that any action will be taken unless significant drivers exist. The question is simply do they pose either an unacceptable risk or an irresistible opportunity? The existence of such drivers does not mean that any response will include coal recovery, and alternatives may appear more favourable in other specific circumstances. The main driver categories are summarised below.

3.1 Environmental and safety

Current approaches to risk may be different to those adopted when some residues were deposited. Consideration is now more likely to be given to the potential for future impacts as well as any immediate and obvious problems. However, for existing situations state intervention is generally only forthcoming where there is an identified issue. Action is unlikely to be funded unless there is no identifiable responsible organisation and the situation pre-dates current relevant protective legislation. In these cases the objective is generally to remediate the site as quickly, cleanly and cheaply as possible and so, often coal recovery is often not considered.

Water pollution: There are several types of water pollution that can result from the stores of coal production residues. The common feature is leaching of pollutants. These include acid rock drainage (ARD) where high concentrations of sulphide minerals are present, and leaching of heavy and in some cases radioactive elements. Doka (2009) carried out a life-cycle analysis covering both mining spoil and coal tailings by modelling both the short (100 y) and long-term (60,000 y) leaching of elements. Arsenic was the dominant contributor to toxicity burdens and was predicted to be larger for tailings than for spoil by a factor of 5 to 6. The mechanisms include interaction between rainwater penetrating inadequately protected piles and leakage of liquid from inadequately sealed or damaged impoundments. Acid drainage has been addressed in various ways. The most obvious approach is to rectify damage to the containment structures though this may be much more easily said than done. Prevention of water ingress by compaction or capping may be possible. Mixing of acid generating residues with alkaline materials such as ash from FBC has also been used as a mitigation strategy.

Air pollution: Both solid and gaseous pollutants can be produced. The disturbance of fine material either from stockpiles of fines or from dried out tailings ponds is the source of the former. Dust suppression can be applied by means similar to those used for coal stockpiles. One approach is to ‘crust’ the surface of the heap using polymer spraying but in many cases the source is capped with soil and vegetated. Oxidation of the organic materials in residues produces gaseous emissions. This oxidation process is ubiquitous for all coals once exposed to air, although the rates vary depending on the coal type and ambient conditions. Generally this is only considered to be an issue if it progresses to combustion. In Ukraine for example it has been estimated that burning coal production residues emit a total of about 500 kt/y sulphur, nitrogen and carbon oxides. On average each burning heap emit; 150 t/d carbon dioxide, 1.5 t/d of sulphur dioxide, 0.4 t/d of hydrogen sulphide, and 0.1 t/d of nitric oxide (Ogarenko, 2010). Walker (1999) provided an extensive discussion of uncontrolled combustion in coals including coal wastes. Again sealing the surface with soil is one approach and this is intended to starve the fire of air but some fires become intense and are difficult to extinguish.

Land disturbance: Reduction in demand for newly mined material, by recovery of coal that has already been extracted may also be viewed as an environmental driver. However, it is only likely to delay new mining operations rather than obviating them altogether. Removal of material already stocked may release sufficient land and thus avoid stocking on to new land.

Safety: Safety concerns are mainly related to the stability of piles or impoundment dams. These issues are associated with the activities of the minerals industry in general. There have been cases of damage to the environment and property and loss of life resulting from the failure of tailings dams and slippage of stock piles. One factor affecting the stability of heaps is that in some cases slurry impoundments have been buried within them (Department of the Environment, 2009). Some of the more notorious incidents have prompted improvements in the quality of new structures. The discharge of some 250 million gallons (~0.95 million m^3) from a coal slurry impoundment near Inez, Kentucky in October 2000, prompted detailed examination by the Committee on Coal Waste Impoundments and others (2002) of the issues associated with coal slurry storage, who proposed methods of reducing risks associated with these structures.

3.2 Commercial

Commercial drivers for recovery of coal from coal production residues come into play as the value of the resources change.

Huge amounts of land are unavailable for use because of a legacy of coal production activities. Shoch and others (2003) reported that 2.4 million ha in the USA were disturbed by mining since 1930. Focusing on residues from coal production Schimmoller and others (1995) indicated over 70,000 ha in the USA and 40,000 ha in Europe were unreclaimed.

A wide range of factors contribute to determining the value of coal contained in residues. For any specific resource there is a point at which a particular recovery and utilisation strategy becomes financially attractive. Often the materials themselves are available at very low or no cost and so such factors as local tax/royalty regimes and the cost of the technology and operations are determining factors.

Companies holding large amounts of residues have the potential to make large savings in their own fuel costs by recovering and using coal from them. In one example, OAO Severstal declared a saving of 25 million roubles through a project recovering their low ash coal slurries for use in their power plant. The cost was around one-third of that for buying and transporting coal from the open market. Their expectation was for this resource to be sufficient for their power plant for around 30 years (OAO Severstal, 2004).

In some cases the recovery of organic coal from residue deposits is not in itself profitable but can provide some mitigation of the costs incurred for land reclamation (Department of the Environment, 2009).

3.3 Regulatory

In some countries coal mining, preparation and residue disposal are covered by extensive regulations which may encourage recovery of coal material though this is not always the case. Mining and particularly surface mining regulations may not be appropriate to the activities that are undertaken to recover coal from residue stocks. Specific recognition of this type of activity in regulation may be necessary to drive recovery projects.

Regulations that limit the scope for disposal of materials may drive recovery of older stocks. For example where planning consents for the extension of tailings impoundments are denied, one option for the operator may be to recover material that has previously settled and free up space for new slurry.

In some countries legislation is in place which demands that reclamation is undertaken as part of the colliery closure process though this may not be controlled by the same body that has responsibility for mining activities. In the UK, for example, local planning regulations now set requirements on the condition to which industrial sites must be returned on closure, whereas mining activities are dealt with by The Coal Authority.

In the EU the Mining Waste Directive (MWD) (The European Parliament and The Council of the European Union, 2006) provides a legal framework within which member states must assess the risks associated with mining waste which fall broadly under the heading 'environment and safety'. In work associated with implementing the MWD it was concluded that of 32 countries studied (EU27, Norway, Greenland, Australia, Canada and USA) only eight had systems for classification of mining waste facilities in place prior to implementation of the directive (DHI Water Environment Health and others, 2007). It will be some time before the impact of this legislation on inactive stores of coal preparation residues becomes apparent, as the inventory is not due to be completed until 1 May 2012.

4 Barriers

Factors that act as barriers to coal recovery may in other circumstances, act as drivers. In particular legislation and regulation may have different effects depending on local circumstances.

4.1 Residue properties

Factors affecting the nature of residues that are deposited are outlined in Section 2.5.2.

The compositional range of the organic coal material in coal preparation residues reflects the global range of coal composition. Residues resulting from the screening of fines from ROM coal are generally of similar composition, though they may have lower inorganic mineral contents if preferential breakage of the organic material occurred during mining. In this case the composition is unlikely to present a barrier to recovery. However the fineness of the material may present challenges particularly for handling and transportation during wet or freezing weather.

Washing processes concentrate inorganic minerals in the residues so the levels are generally significantly higher than in the ROM coal. The point at which this is considered as an insurmountable barrier has changed as techniques for reprocessing or utilising these materials have developed. Companies that undertake recovery operations generally set a clear cut-off for the minimum proportion of organic coal that must be present for an opportunity to be pursued (*see* Section 5.1). However, for some components the concentration effect can present a significant increase in the hazards that preparation residues present. Some coal deposits are associated with significant levels of radioactive elements. For example in the Almaty region of Kazakhstan, the United Nations Economic Commission for Europe (2000) reported that 15,000 t of radioactive coal material have been stockpiled from a brown-coal mine, with the levels in the coal fines being five times more concentrated than in the raw coal. It is not clear whether this should be considered as a barrier or driver to dealing with this residue. The identified threat is from wind dispersion of the fines but working the material would also present significant safety considerations.

Moisture levels in washery residues are generally high and so they can present significant materials handling challenges, as can dry fines. The moisture content also limits the range of options for utilisation as some processes cannot accept slurry, or drained slurry, either for technical reasons related to feeding or because of the impact on process conditions/economics of evaporating large amounts water in the process.

Once removed from the ground and exposed to air, coal starts to degrade through oxidative processes. The loss of calorific content through this process is often very slow although where materials have been stored for many years it may have become significant. Coking properties on the other hand decline much more quickly due to oxidation.

The rate of oxidation of stocked coal and coal residues is affected by numerous factors, the key ones being oxygen availability and heat dissipation rate. These are linked and depend on the permeability of a stack and air flow patterns. Where heat generation exceeds heat dissipation, temperatures increase and reaction rates accelerate leading ultimately to combustion. Whilst removal of a smouldering or burning residue deposit may be highly desirable from a health and environmental perspective, it may be too hazardous for coal recovery activities to be undertaken. Efforts to compact and cap deposits, to prevent air ingress, may be possible.

4.2 Location of material and method of storage

Coal production residues are generally deposited close to the point of extraction and whilst the parent mine or group of mines remain operational access to the material is likely to remain open. The mode of disposal of some material and subsequent local developments restrict or prevent future access.

Where sites have already been reclaimed (without coal recovery) further disturbance may be environmentally unacceptable. Capping of piles and dried out tailings impoundments followed by re-vegetation is a common approach to dealing with the issues that these sites present and often prevents future access for coal recovery. However, some works carried out in the past are now considered of a low standard and so opportunities to recover coal may arise if further remediation of the land is found to be necessary.

Industrial centres have often developed around locations where coal was readily available. So residues are now located within areas of human habitation/business operations and further activity might be unacceptable, with popular opposition and local planning regulations presenting barriers to accessing material.

Even away from population centres residues may have been adopted as locations for leisure activities or become recognised as national landmarks/monuments (Khan and others, 1986). Material may be viewed as performing a useful function so that there are mixed views when removal is proposed with welcome for a cleaner environment but concern over for example the loss of wind protection that residue heaps provide.

In Wales an application to remove a spoil heap, recover useful coal and rehabilitate the site providing a museum and land for domestic and commercial building followed a long planning appeals process before being granted in August 2010. A key argument from opponents was that the heap was of historical significance as a reminder of the industrial history of the area (Hull, 2008; BBC, 2010) although there were also concerns over the amount of traffice that would be associated with the operation.

The original method of deposition of the residues affects the scope for future recovery of them. One approach is to place residues in cavities resulting from the mining activities. Where this includes injection of materials in the form of slurry or paste into underground mines there is no realistic prospect of future recovery. Even where materials are accessible such practices as co-disposal of coarse and fine washery residues, perhaps also with general mining spoil or fly ash from nearby power plants can present significant challenges for reprocessing this material to recover the organic coal content.

Some residues have been dumped with other colliery wastes onto beaches or into the sea. This practice presents difficulties in reclamation of useable coal. It was common in the northeast of England where evidence of it is still visible. However, it was not confined to the UK, and examples can be found around the world where coal production occurs in coastal areas.

The act of recovery of organic coal material from residue deposits can be seen as a barrier to the final reclamation of land that may delay this process for years (Department of the Environment, 2009). Where the drive for land reclamation takes precedence the opportunity for coal recovery is likely to be lost permanently.

4.3 Regulatory issues

The prevailing regulatory framework has a strong effect on the viability of recovery of coal from production residues. Regulations specifically designed to control mining operations may not be applicable to the activities needed to recover stocked material. Environmentally beneficial effects may not be recognised within the framework, and the way in which the materials are classified (whether it is 'coal' or 'waste') may constrain the options for recovery. In some cases specific requirements may present barriers to coal recovery from residues.

In the USA several significant federal laws are applicable as well as state level regulations which must also be considered. The 1977 US Surface Mining Control and Reclamation Act (SMCRA) deals with the responsibilities of operators of surface mining activities and the of requirements for water released from sites are of particular relevance. Potentially operators may find that they must address issues caused by those who deposited the coal production residues. These issues may only become apparent during work on the site. Concerns over the potential cost, and the possibility that the issues may be impossible to address, provide a significant barrier to some coal recovery projects. Various states have sought to overcome this issue through putting exemption mechanisms in place.

The US EPA rule 'Identification of Nonhazardous Secondary Materials That Are Solid Waste' under the Resource Conservation and Recovery Act (RCRA) defines solid waste and also finalises a definition of traditional fuels (US EPA, 2011b). The solid waste definition will determine whether a combustion unit must meet the emissions standards under the Clean Air Act for 'solid waste incineration units' or for 'commercial, industrial, and institutional boilers'. Development of this rule provoked extensive comment from boiler operators (Bessette, 2010). The wording of the rule has the potential to present a significant barrier to the use of coal recovered from abandoned coal residue stocks.

Coal extracted is generally subject to some form of tax or royalty. The level at which these are set can have a strong influence on the viability of coal recovery projects and as such form a potential barrier. Adjustment to legislation may be required to remove such barriers, or at least lower them if such projects are to be encouraged. Some US states have mechanisms in place which can provide tax breaks or exemptions (West Virginia State Treasurer, 2010; Burnett, 1993).

The sheer amount of legislation to be considered may prove to be a barrier. Whilst ultimately commensurate with activities of primary mining, and within the competence of traditional mining companies, this may prove to be disproportionate for the smaller and less complex operations concerning coal recovery from residue stocks. Castrilli (2007) carried out an extensive overview of Canadian legislation/regulation relating to abandoned/orphaned mines. In this he considered the applicability of 14 federal laws (with national or regional applicability) plus numerous provincial laws dealing with resources and mining and with the environment. Whilst some of these may not be relevant to coal recovery it serves to illustrate the potential complexity which an operator may face.

When an impoundment in Tennessee was approaching capacity, the option for removal of and sale of fines to extend its life was excluded from consideration, largely on the basis of the permitting process which was estimated at a cost of $300,000–500,000 with a lead time of 2.5 years (Nida, 2004).

The EU MWD (The European Parliament and The Council of the European Union, 2006) places various obligations on member states. Relevant excerpts from the articles of the directive are set out below.

Article 1 states that: 'This Directive provides for measures, procedures and guidance to prevent or reduce as far as possible any adverse effects on the environment, in particular water, air, soil, fauna and flora and landscape, and any resultant risks to human health, brought about as a result of the management of waste from the extractive industries.'

Article 4 sets out the general requirements as:

1 'Member States shall take the necessary measures to ensure that extractive waste is managed without endangering human health and without using processes or methods which could harm

the environment, and in particular without risk to water, air, soil and fauna and flora, without causing a nuisance through noise or odours and without adversely affecting the landscape or places of special interest. Member States shall also take the necessary measures to prohibit the abandonment, dumping or uncontrolled depositing of extractive waste.

2 Member States shall ensure that the operator takes all measures necessary to prevent or reduce as far as possible any adverse effects on the environment and human health brought about as a result of the management of extractive waste. This includes the management of any waste facility, also after its closure, and the prevention of major accidents involving that facility and the limiting of their consequences for the environment and human health.

3 The measures referred to in paragraph 2 shall be based, inter alia, on the best available techniques, without prescribing the use of any technique or specific technology, but taking into account the technical characteristics of the waste facility, its geographical location and the local environmental conditions.'

Article 20 states that: 'Member States shall ensure that an inventory of closed waste facilities, including abandoned waste facilities, located on their territory which cause serious negative environmental impacts or have the potential of becoming in the medium or short term a serious threat to human health or the environment is drawn up and periodically updated. Such an inventory, to be made available to the public, shall be carried out by 1 May 2012, taking into account the methodologies as referred to in Article 21, if available.'

Member states will interpret these requirements though whether this will result in coal recovery or resource sterilisation is unpredictable and dependent on local conditions.

4.4 Capacity issues

In addition to the specific areas discussed in this chapter there is a less easily defined issue which relates to the knowledge and resources of communities and officials.

In work on development of a model for removal of GOB piles the Western Pennsylvania Coalition for Abandoned Mine Reclamation (WPCAMR, 2001) found that where the piles were of long standing and vegetated there was a significant level of ignorance as to their nature and the need for removal and reclamation. This included both local populace and local officials. Even where officials were aware of the issues they were often ill equipped to deal with them. Some owners were unaware of where they could gain assistance in addressing the problem and were wary of any involvement with environmental agencies.

5 Opportunities

This section covers the stages from identification to realisation of opportunities to utilise coal production residues. Section 5.1 covers the assessment phases, 5.2 the recovery of concentrated organic coal from store and the remaining Sections 5.3 to 5.5 outline various options for utilisation.

5.1 Identification and assessment of resources

When dealing with materials that were deposited many years, or even decades ago, the first challenge is to identify their location. In general in the more distant past formal recording of this information was not undertaken in a consistent manner, if at all. So, subsequent growth of vegetation or construction of buildings can make deposits difficult to locate. Even when they remain as obvious marks on the landscape there are unlikely to be records of composition. For more recent activities records tend to be better, though this varies from country to country.

Once a coal production residue deposit has been identified the initial assessment of the opportunity requires knowledge of the:
- amount of material in place;
- composition of the material and washability.

Mining records and permits may provide some of the necessary background information enabling determination of (Kent and Risch, 2006):
- site vintage (years it was mined);
- seam or seams from which the coal was mined;
- methods of mining and preparation used during the time the pile was active;
- extent of the deposit (from surveying or aerial photography).

This information will inform a decision on whether site evaluation and resource sampling are justified. The approach used by the Mineral Development Corporation (MDC) in the USA involved a four-stage process to assess the value of slurry residues (Henry and others, 1995):

1 Visual inspection:
  - preliminary assessment of slurry quantity;
  - visual assessment of slurry quality, such as rough estimate of particle size;
  - site characteristics, such as access, availability of services, scope for disposal of residues from reprocessing.

2 Initial drilling and analysis:
  - three or four core samples to provide approximate representation of pond;
  - estimate of total resource;
  - short particle size distribution;

3 Short gravimetric float sink analyses on initial core samples:
  - three densities;
  - estimate yield and product quality;

4 Full evaluation/feasibility:
  - extensive drilling;
  - detailed size analysis of each sample;
  - extensive (10 densities) gravimetric float/sink analysis of each size fraction;
  - mining plans;

- permit investigation/application;
- other engineering/feasibility studies.

The results at each stage determine whether the process should move to the next stage.

5.1.1 Preliminary identification

Some information on the location and quantity of resources has been collected in registries or through inventorying processes. Often they are not exclusive to coal but cover tailings impoundments, or heaps from mining activities in general. They usually have a specific purpose such as recording high risk (health, safety, or environmental) stores and thus do not provide a comprehensive record of the amounts and locations of all such residues. For example the registry operated by International Commission on Large Dams (ICOLD) includes tailings dams of all types as well as reservoirs.

Cal Data Ltd (2005) included an extensive survey of abandoned mine databases in a report for Canada's 'National Orphaned/Abandoned Mines Initiative'. It identified localised databases for most US states as well as those at Federal level and one in Iran. The overall situation in various other countries (Australia, South Africa, UK, Sweden, Japan, Chile and Ireland) is summarised although the information is not specific to coal mines.

The EU MWD calls for an inventory to be made by each member state. It is likely that only sites already identified as posing specific threats or already causing environmental damage will be listed in it. That is the case for the UK (Potter, 2011) though other member states may take different approaches. The inventories need to be submitted to the Commission by 1 May 2012 but it seems likely that they will provide much information about sites with potential for recovery of coal production residues.

Several inventories are operated in the USA. The main national inventory of relevance is the Abandoned Mine Land Inventory System (AMLIS) operated by the Office of Surface Mining – Reclamation and Enforcement (OSM) (www.osmre.gov/aml/amlis/Description.shtm). AMLIS is incomplete as:

- only high priority coal mining related problems have been systematically inventoried;
- some states and Indian tribes have not always been able to inventory all their high priority (Priority 1 and 2) coal mining related problems because of resource limitations;
- only includes problems eligible for funding. Many are currently ineligible.

The AMLIS is dynamic and coverage changes because:

- ineligible problems become eligible through deterioration, influx of people to a previously remote area, or some other factor;
- new problems arise, such as fires, subsidence holes, and landslides.

The information includes location and size (area) for piles, embankments, impoundments and slurry. There are several thousand features of this type recorded including projects that are completed, current or awaiting funding.

Other inventories and registries in the USA are local initiatives focused on a single state or part of a state. Various approaches are taken to developing these.

WPCAMR developed an inventory and the listing includes fields for specific energy content and volumetric size of the pile and is of some value for identifying and estimating amounts of residues (WPCAMR, 2001).

The Coal Impoundment Location and Information System (CILIS) (www.coalimpoundment.org) lists impoundments in:
- Kentucky;
- Ohio;
- Pennsylvania;
- Tennessee;
- West Virginia.

Record fields in the database include:
- ID number;
- owner;
- height;
- maximum capacity (area and volume);
- latitude;
- longitude;
- inspections.

South Africa's coal production residues, duff coal and discard, were inventoried in 1985 and again in 2001when a summary report was published (Department of Minerals and Energy, 2001). The 2001 inventory exercise updated the situation against the baseline established at 1985. The inventory exercise was based on questionnaire responses and compared to information from monthly returns from collieries. The information collected by the survey does not completely match that based on the returns to the Department of Energy and Minerals. Some smaller mines did not respond, one group was in liquidation and some mines changed their production so that the annual result differed from the questionnaire estimate. Questionnaires covering 142 'discard and slurry disposal facilities' were returned which was considered to represent >90% on a tonnage basis. Reasons for not returning questionnaires were:
- no discard or slurry production;
- colliery closed;
- information too sensitive.

The inventory database is not generally accessible as it includes confidential information. The reports provided summary and analysis of the data collected.

Where no relevant inventory exists more fundamental approaches are needed. When an assessment was made of the resources in Indiana this was largely based on extracting data from historical mine records (R E Mourdock & Associates, LLC, 2006). Their methods were:
- compile information on coal preparation plants in Indiana;
- use historical and aerial photos to map the locations of preparation plants;
- use historical aerial photos to identify and map the slurry cells associated with the preparation plants;
- compile data that can be used to estimate the volume of material present;
- evaluate the current 'reclamation' status of the slurry ponds.

5.1.2 Investigation

Once the existence of a deposit is identified a process of investigation follows:
- the material deposited in heaps will have been influenced by market conditions (for example, coal quality requirements, supply and demand balance) from time to time on the one hand and the availability of technology on the other. Many stocks of coal production residues have had material of different qualities deposited on them over time (*see* Section 2.5.2);
- random sampling of anthracite culm banks in the Monongahela River drainage basin, in the USA, demonstrated the wide range of compositions that can occur in such stocks (*see* Figure 1.

An extensive survey by Cobb and others (1979) of coal slurry residues at one site showed significant

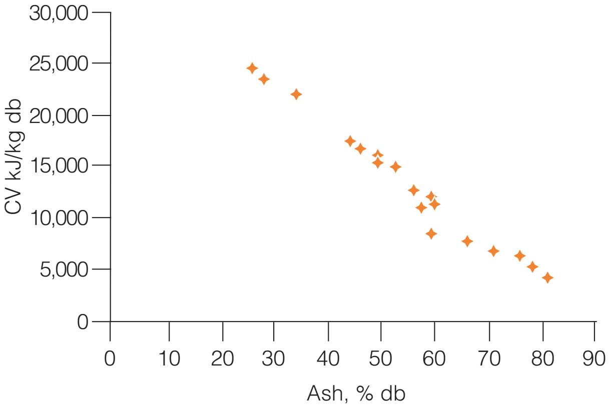

Figure 1 Spread of ash and energy contents in some randomly selected coal waste banks located in the Monongahela River drainage basin (Leonard and Lawrence, 1973)

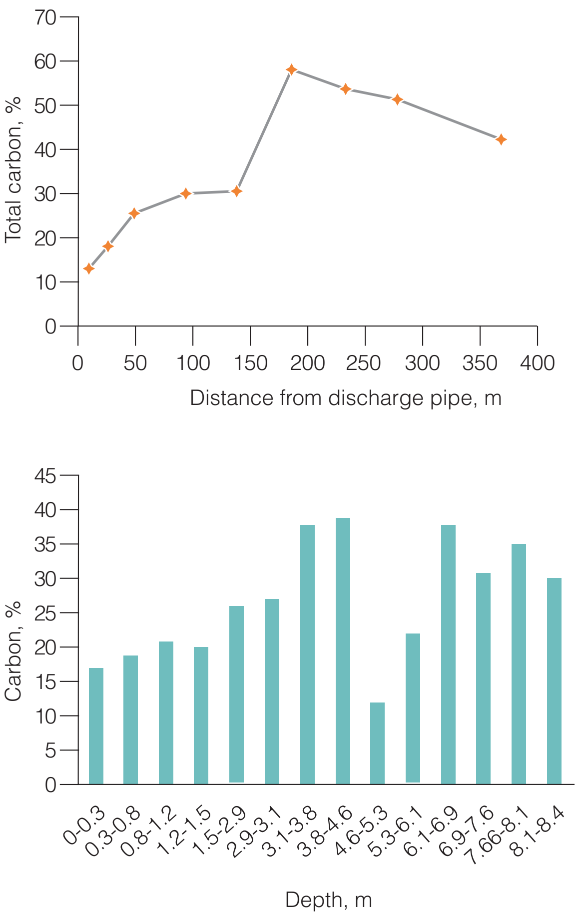

Figure 2 Variation in carbon content in a slurry deposit (Cobb and others, 1979)

variation in the composition of the material deposited. Figure 2 shows the results for a single traverse along the centreline of the deposit fan moving away from the discharge point, and for a single borehole sample taken from close to the discharge point.

An accurate assessment of the content of a stock can only be gained by surveying the resource. A variety of approaches have been tried but the most common is for extensive targeted sampling and analysis of the stock to be undertaken. Such uneven distributions of organic coal and inorganic mineral matter in ponds as illustrated in Figure 1 and Figure 2 means that large numbers of samples are often required for accurate mapping of the contents.

An application for exemption from 'Abandoned Mine Reclamation Fees' at the Sunnyside refuse pile, Sunnyside, Utah (Burnett, 1993) was based on the assertion that the material in a refuse was of zero value. To support this, information from several surveys was presented:

(i) September 1987: 13 holes from 13 to 120 ft (~4.0 to 36.6 m) deep, 52 samples at 10 ft (~3 m) intervals;
(ii) March 1991: 11 holes, 109 samples 10 ft (~3 m) intervals;
(iii) September 1992 extra data collected and consolidated with 1991 data: 96 new samples.

The results are summarised in Table 5.

A small proportion of fine material (estimated at 16%) was found. The average properties from the surveys of the heap showed a significant variation over a range of about 10%.

An estimate of the amount of material, the surface profile and the profile of the underlying land is needed. Since the 1969 Mine and Quarry Tips Act in the UK, operators have been required to measure and record the profiles of heaps on an annual basis and thus it is possible to estimate the amounts deposited since then. This is an unusual situation and the underlying profile is often known only approximatelyif at all. However, it is usually clear when the underlying surface is reached during extraction of borehole samples. Therefore the depth at each sampling location can be estimated and used to map a crude profile of the underlying surface.

Table 5 Summary of borehole surveys at the Sunnyside refuse pile, Sunnyside, Utah (Burnett, 1993)				
Survey	No of boreholes	No of samples	Mean CV, kJ/kg	Mean ash, %db
September 1987	13	52	14421	50.14
March 1991	11	109	12951	55.19
September 1992	–	109+96	13600	53.20

Geophysics techniques have been used to investigate the underlying structure of coal slurry impoundments. Kaminski and others (2006) investigated both airborne electromagnetic surveying and DC resistivity profiling for identification of structural problems in impoundments which could be indicative of increased risk of failure or leakage of fluid. Features identified using these techniques may be of importance for ensuring that extraction of material from impoundments is carried out safely. For example the presence of areas of unconsolidated slurry deep within impoundments was detected. However, the measurements also enabled mapping of the underlying ground profile although there were some limitations, such as the 50 m limit to the resistivity survey range.

An estimate of the average bulk density of a deposit may be obtained either from measurement of the bulk density of core samples or by assuming a typical average bulk density value. To estimate the solids in coal slurry Beard Technologies applied an average bulk density of 56 lb/cu ft (about 900 kg/m^3) (Henry, 2006).

Multiplying the volume and bulk density estimates together provides an estimate of the mass of material. For robust estimates of the amount and organic coal content of stored coal production residues individual site assessments are necessary.

5.1.3 Decisions

Clear decision making processes are essential if recovery projects are to be selected successfully. The potential operator needs to define the required properties of the materials, taking into account their potential market, coal preparation capabilities and overall costs.

The process can be summarised using decision trees. Harrison and Akers (1997) considered fine coal waste as a resource and set out decision trees describing the process of assessment of the technical and economic viability of the resource (*see* Figures 3 and 4).

Decisions on whether to proceed with coal recovery projects need to made against clear parameters which define the requirements for a viable project. Beard Technologies set out their guiding rules for proceeding with coal recovery projects form slurry impoundments as (Henry, 2006):
- minimum of 1 Mt raw material in impoundments;
- minimum of 30% recovery of +200 mesh size slurry material;
- maximum ash content of 40% in raw slurry material.

These parameters chosen and the cut-off points depend on the recovery practices and technologies (*see* Section 5.2), the associated costs and the potential markets for recovered material.

5.2 Recovery and reprocessing

Coal preparation residues cover a wide band of compositions and have been deposited in different ways in many different locations. Each situation needs to be assessed and treated individually. Various

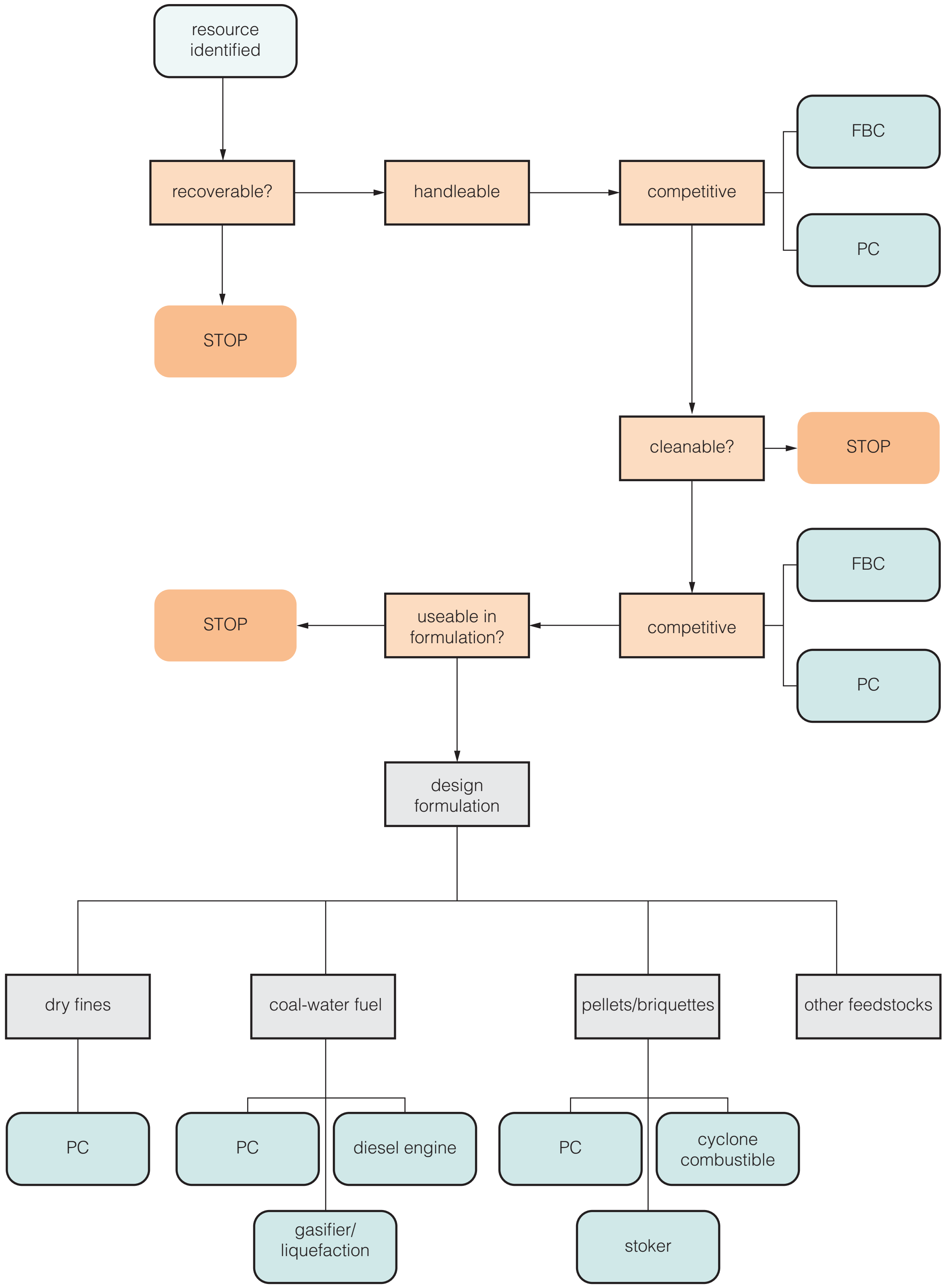

Figure 3 Technical viability decision tree for slurry recovery projects (Harrison and Akers, 1997).

techniques have been applied to both recovery and reprocessing of these materials.

One of the key issues for projects of this type is the set-up cost. Capital investment in coal washing associated with coal mining generally can usually be amortised over 25 years or more. In the case of

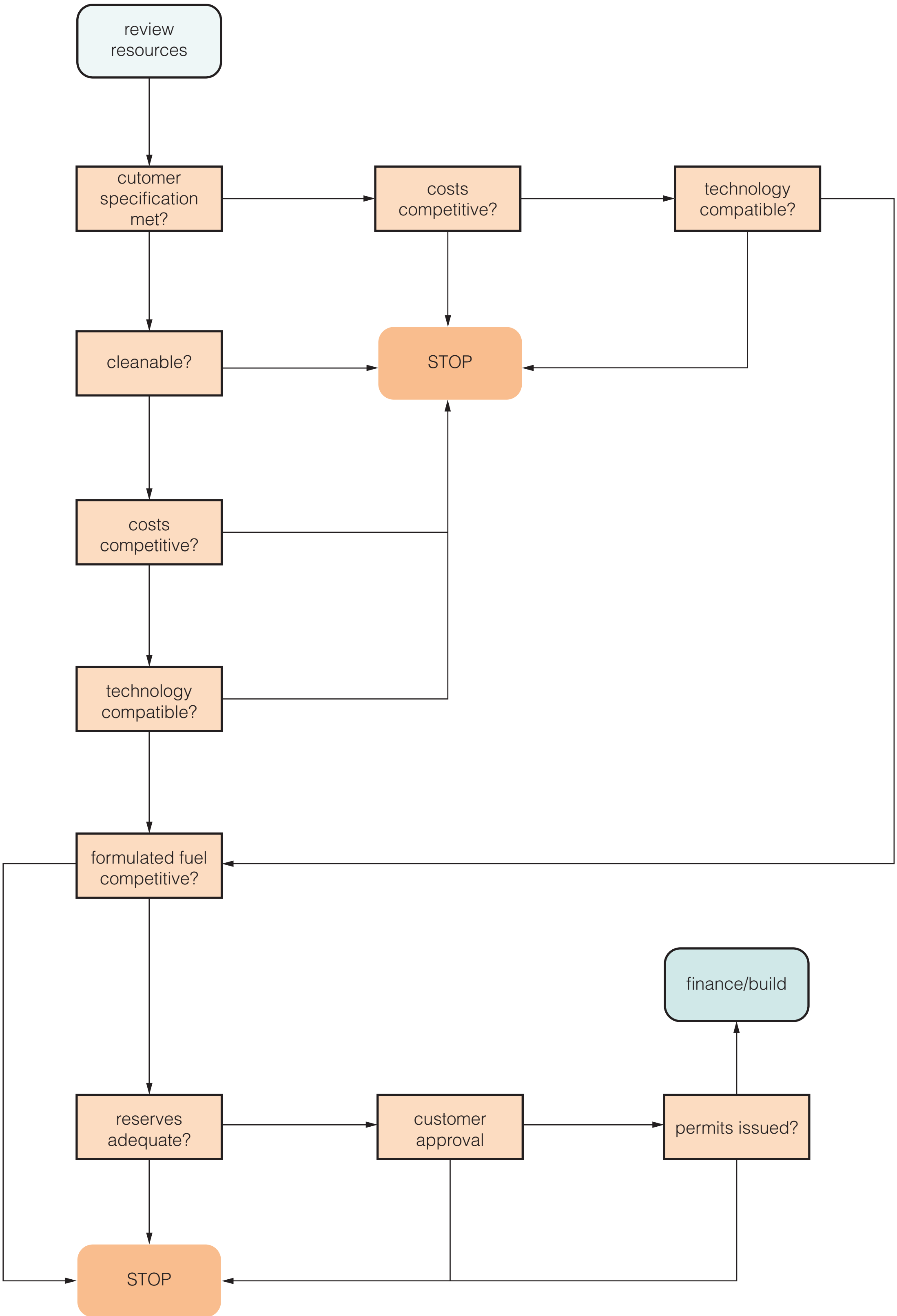

Figure 4 Financial viability decision tree (Harrison and Akers, 1997)

coal production residues the resource at any one location is not usually sufficient to last more than 5–10 years and often is much less. So in general, the technology used must have either a much lower cost or be transportable between locations so that its cost can be written off over multiple projects. The latter is the usual approach adopted.

5.2.1 Recovery from storage

Various companies offer recovery equipment or carry out recovery as a service. For example in Australia, Superior Coal Limited offer a service which includes surveying, hydraulic mining of deposits and processing to provide a product as either dewatered filter cake or briquettes (Superior Coal, 2010).

Other companies procure sites which they then work; extracting, reprocessing and either selling or utilising the coal concentrate.

The most basic approach is to dig out dried materials with heavy machinery, such as backhoes and front-end-loaders. Success depends on the state of the material, and the topography of the location which determine whether it can be accessed by the necessary equipment.

Dredging material from impoundments is a common approach for wet impoundments. If this is undertaken at a site with a modern preparation plant in operation, coal lost in the past can be reclaimed as a part of normal operations (Liquid Waste Technology, nd). Even where an impoundment has dried out addition of small amounts of water may be sufficient to facilitate this approach to fines recovery (Liquid Waste Technology, nd). Although each impoundment needs to be dealt with individually, according to Henry and others (1995) the typical procedure adopted by Mining Development Corporation when applying their combination of hydraulic re-mining with dredging, was:
- lower water level to expose about 20 ft of face (~6 m);
- wash slurry from the face with high pressure water jets forming a beach of partially liquefied slurry;
- recover the slurry with the dredge.

This process is illustrated in Figure 5.

This approach slumps the slurry in a controlled manner and allows the dredge to be positioned at a sufficient distance that if a sudden collapse occurs it will not be affected.

Hydro-shear technology was developed by DTE Peptech Inc to both recover from storage and to initiate the separation of coal matter from clays and other fine mineral particles. This was developed as a small, frame-mounted module that could be easily transported to site and then lowered by crane onto the impoundment to be recovered. A nozzle near the base of the unit emits a high intensity water jet towards the slope of the coal residue. The shearing effect of this jet initiates the separation process. A slurry is formed which flows under the unit where it is extracted by a slurry pump via an eductor. It is pumped away for washing to produce an organic coal concentrate. The ejector nozzle can be rotated in the horizontal plane enabling the jet to be swept across the base of the residue. Gradually the

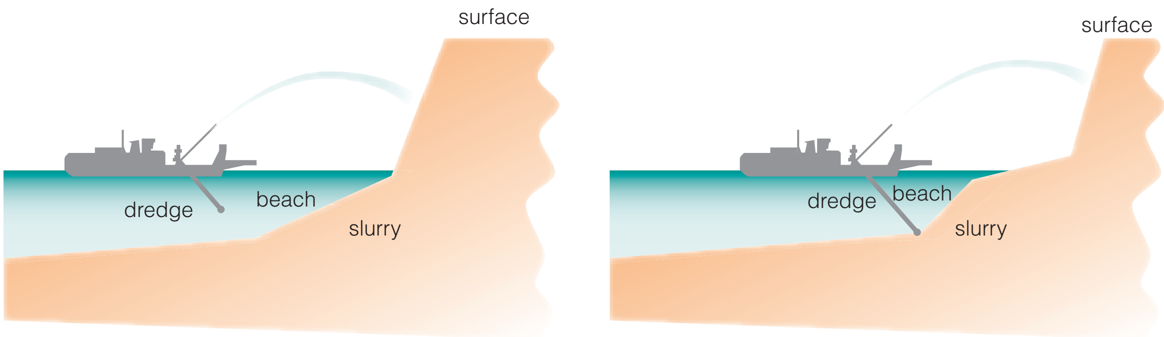

Figure 5 Hydraulic mining and dredging for recovery of coal slurry deposits

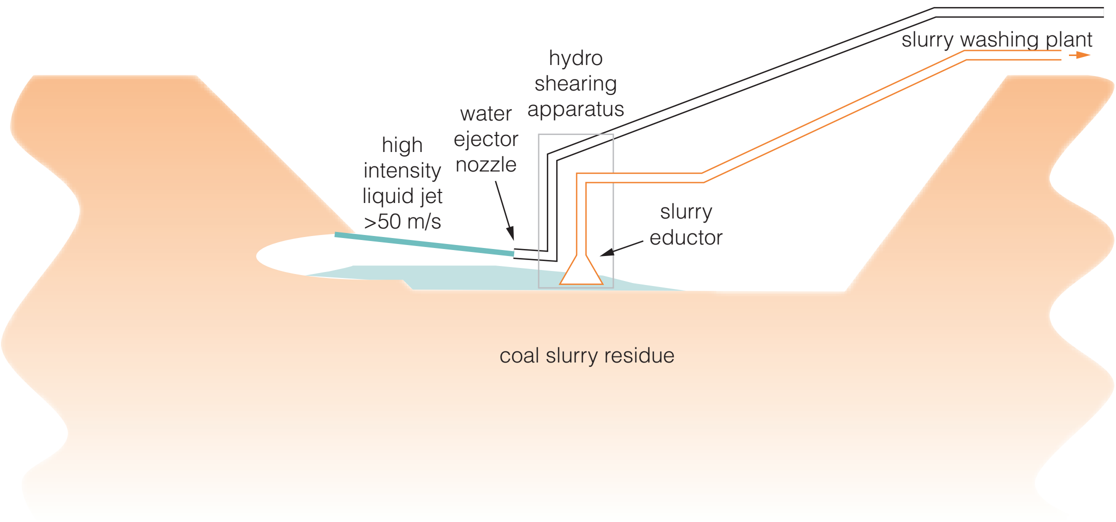

Figure 6 Coal reclamation apparatus and method DTE PEPTEC Inc (Glista, 2008)

material higher up is undermined and slumps towards the base. Downward facing nozzles enable slurry residue below the unit to be liquefied and removed so that the unit can move down through the impoundment so the material at lower levels can be recovered progressively (*see* Figure 6).

An early project expected a recovery rate of 0.5 Mt/y from fine coal slurry pond at DTE Dickerson LLC containing 4–5 Mt (AICE, 2004).

5.2.2 Separation of coal from recovered material

Coal cleaning technology has undergone a process of continual development with a combination of refinements to existing techniques and development of new ones. The level of processing from which the residues resulted is equally various so there is no single definitive approach to reprocessing.

Density based separation techniques

Developments have made it possible to recover more organic coal material from coal residues. Many older stockpiles have been rewashed in the past and still left carbon contents of 6–8%. Further washing with current techniques, such as RecyCoal's natural medium density separation system, can result in residues with only 1–2% carbon (Tinnion, 2011).

Teeter Bed Separation (TBS, also referred to as Stokes Hydrosizing) has been used since 1934, originally for separating on size for mono density particles. These systems have been used for coal recovery from waste piles and tailings lagoons since the 1960s and used to treat ROM coal in the UK, US and Europe since the 1980s. Increases in the sizes of DMC installed in South Africa have raised the bottom size recovered from 0.5 mm to 3 mm and TBS has been tested as an option for recovering this sub 3 mm fraction (Hand and Craddock, 2005). The tendency of particles finer than 250 µm to float in these devices, regardless of inherent density, limits their applicability for treatment of the fine material deposited from coal slurries.

Density-based approaches are generally applicable to coarser materials such as spoil, which are not the main focus of this report.

Flotation based separation techniques

Froth flotation as a mineral preparation process has been in existence for over a hundred years and was extensively reviewed by Maurice and others (2007). Froth flotation for recovery of fine coal is widely used in modern coal preparation plants with around 13.6% of global cleaning capacity supplied by froth flotation (Laskowski and others, 2007). It is typically most effective in the

10–100 µm particle size range. The factors that affect the effectiveness of the process are broadly related to the adhesion of the coal particles to the bubbles. For this to occur, the particles must both encounter a bubble and have the necessary surface characteristics to adhere to it.

Sufficient residence times are required to ensure these processes occur. Multiple sequential flotation cells or relatively tall flotation columns are used. These are difficult to transport thus, limiting their applicability for reprocessing of fine coal residues. Various operation and design approaches are taken to mitigate this problem and enable flotation devices to be used for this purpose.

Chemical additives (frothing agents and collection agents) are introduced into the process to promote the necessary conditions. Various developments have enabled more effective recovery and improved process efficiency by (for example) reducing the additive demand.

Various methods of bubble generation and introduction to flotation cells/columns have been developed. High intensity flotation cells use forced air (such as the Bahr and Microcel™ cells) or induced air flows (such as the Jameson and XPM cells) to generate microbubbles (tens to hundreds µm diameter), forming high intensity contact zones to promote adhesion of the coal particles to the bubbles.

The use of water with CO_2 dissolved in it under pressure was investigated as an alternative approach to microbubble formation. When the fluid is fed to the flotation column a slightly finer bubble size was generated compared to that from conventional mechanisms. Shiao (1993) derived 'separation efficiency' as :

separation efficiency = Btu recovery + pyrite rejection – 100

Using this relationship, laboratory-scale performance of 'dissolved CO_2' froth flotation was compared to compressed air microbubble flotation in a 2" (~50 mm) diameter test flotation column. The feed stock was underflow from a coal cleaning process thickener. However, the results showed only a slightly greater separation efficiency of 49.2% compared to conventional microbubble flotation which gave 47.3%.

In laboratory studies Tao, and others (2008) found that introduction of very small bubbles (<1 µm), referred to as 'picobubbles', into the process improved recovery by 10% for highly floatable and up to 40% for poorly floatable coals. The picobubbles were introduced into the slurry stream just before it entered the flotation column. They adhered to the coal particles and acted as secondary collectors improving bubble/coal adhesions. Ultrafine material is able to adhere without the need for a collision. This technique also has a lower requirement for hydrophobising additives.

The Imhoflot G cell flotation technology offers a small footprint, low height, device which has the potential for easy relocation from site to site as fine residues are exhausted. It achieves a unit with a low height compared to flotation columns by tangential injection into the flotation chamber. A typical arrangement would involve conditioning the slurry using an attrition stage followed by classification. The slurry would then pass via a storage tank through two G cells in series before froth separation and recovery of the product with a steel belt filter press (Battersby and others, 2003).

Maelgwyn Mineral Services marketed this technology with significant supporting demonstrations undertaken with potential customers, no units were deployed. At the time the main barrier remained the cost and relatively low value of coal. More recently, demand has risen driving up coal price and the technology may now be cost-effective (Battersby, 2011).

Laboratory studies of the use of bacterial or fungal cultures to enhance the separation of organic coal from inorganic minerals in coal slurries demonstrated that this technique could be used to produce enriched slurries. The cultures bind to the lipophilic coal material to improve separation (Shevkoplyas and Litvinenko, 2000). However, the technique has not progressed beyond the laboratory.

Dewatering and drying

Dewatering is energy and time intensive but is crucial to the successful reprocessing of fine coal preparation residues. Various techniques are used in coal preparation plants including: filtration, centrifugation, thermal drying and combinations of these and other techniques as well as the introduction of various types of additives. Various developments have been researched attempting to address this problem some of which may be applicable in reprocessing of fine coal preparation residues.

Water surface tension and contact angle with the coal surface influence the work required to remove water from fine coal. Reduction of the capillary pressure required to remove water from a fine coal filter cake reduces the work required. Additives must increase contact angle and reduce viscosity in order to reduce capillary pressure. Surfactant additives can be categorised according to their hydrophile-lipophile balance (HLB). Those with high HLB are effective at reducing contact angle and promoting coal wetting. Their effects can be conflicting, reducing viscosity but at the same time reducing the contact angle. Many common dewatering agents have high HLB numbers (>15) and in some cases may increase the moisture content of filter cakes. The effects of additive concentration are not necessarily linear, so there may be an optimum concentration. Yoon and Luttrell (2008) reviewed the background science and undertook extensive testing (laboratory and field) with a range of additives and devices.Using samples of slurries from coal preparation plants, additive performance was found to deteriorate with time which it was concluded resulted from oxidation of the coal surface. This has implications for reprocessing of recovered fines from old impoundments. Some surface abrasion of the solids may be required if standard dewatering aids are to be effective. Three groups of additives were investigated at bench scale:

(i) low HLB number (<15) surfactants;
(ii) natural products;
(iii) modified natural products.

Numerous formulations with both individual additives and combinations were investigated at laboratory scale using simple vacuum and pressure batch filters. The effects of other parameters (vibration, surface tension, filter cake thickness, particle size increase due to coagulation) were also examined. At pilot-scale performance of additives with four types of filter was investigated:

(i) 10” (~250 mm) diameter Sepor vacuum drum filter;
(ii) 24” (~600 mm) diameter Peterson vacuum disc filter;
(iii) 6” x 6” (~150 x 150 mm) horizontal belt filter.

Their work culminated in design, fabrication and operation of a proof-of-concept plant for reclamation of impounded coal tailings (*see* Figure 7). The plant was operated successfully and benefits of novel dewatering agents were demonstrated. Product moisture content was reduced substantially as was the power drawn by the disc filter vacuum pumps.

A key parameter determining the effectiveness of dewatering on filters is the permeability of the filter cake formed. Attempts to modify the overall particle size distribution and consequent packing in the filter cake have included investigation of co-processing of biomass with fines to improve coal washing characteristics such as dewatering and froth flotation (Honacker, 2005; Chen and others, 2003). In general this has been unsuccessful.

Conventional filtration technologies can be ineffective for cleaning fine coal as filter media are rapidly blinded. ‘Baleen technology’, a development in micro-screening, enables fine coal tailings slurry to be filtered with fine clay material (slime) removed with the filtrate leaving a coal rich residue. This is dislodged and washed from the screen continuously by a pair of high pressure low volume water jets (Evans, 2008) (*see* Figure 8).

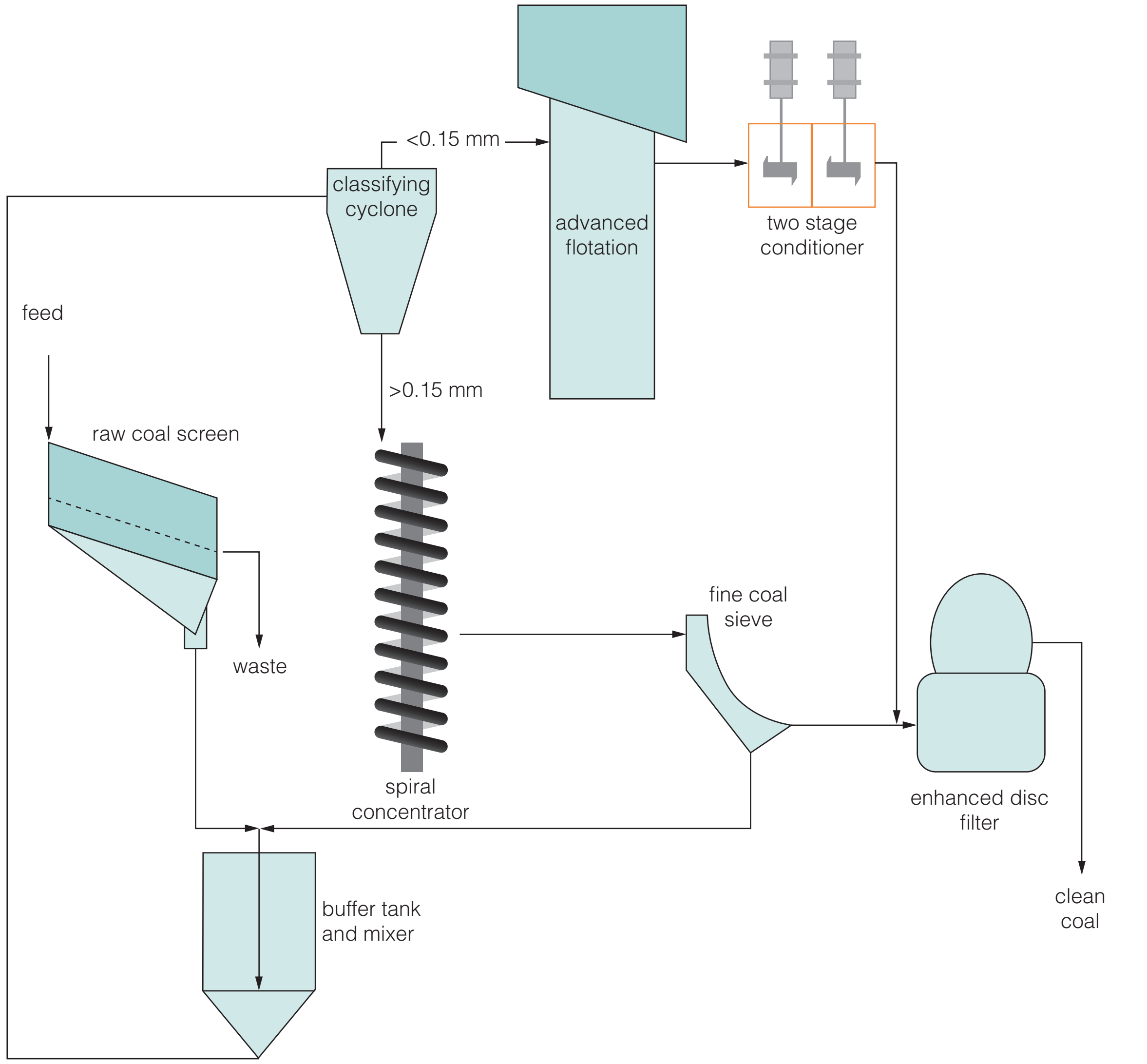

Figure 7 Generic POC flowsheet for treating pond reclaim material (Yoon and Luttrell, 2008)

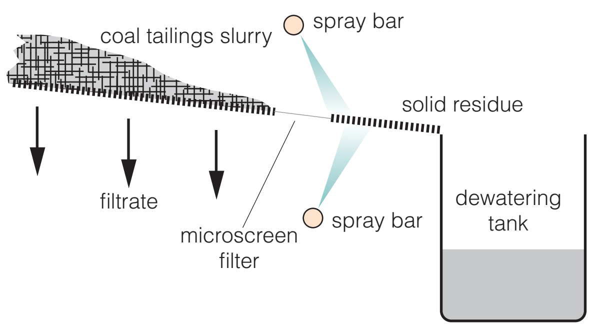

Figure 8 Baleen microfiltration process (Evans, 2008)

A pilot-scale demonstration version has been tested at several collieries in South Africa on thickener inlet material with significant reductions in ash content achieved (*see* Table 6).

The product is typically of a consistency that can be dug with a spade with minimal free water.

Differential Hardness Separation (DHS) technology was originally developed for the kaolin production industry, marketed by Advanced Primary Minerals (patent pending). Greenfields Coal Co has obtained rights for the process and applied it to the cleaning of fine coal residues (Fiscor, 2010).

DHS is a multistage process including milling, heat/air flow drying and separation stages (Figure 9). The system accepts a feed with top size up to 25 mm. The hot air from a gas burner aids drying as the material passes through the first selective pulveriser which grinds the organic coal material preferentially thus assisting the separation of the harder material (mainly silica) at the first

Table 6 Baleen filter trials on South African CPP thickener feeds (Evans, 2008)

Trial	1		2	
Screen aperture, µm	140	125	140	90
Feed CV, MJ/kg	17.66	19.55	19.96	18.93
Product CV, MJ/kg	23.75	24.05	25.35	24.84
Feed ash, %	41.00	33.63	31.44	35.54
Product ash, %	22.16	20.52	19.15	19.79
Mass recovery, %	80.03	86.90	53.55	62.80

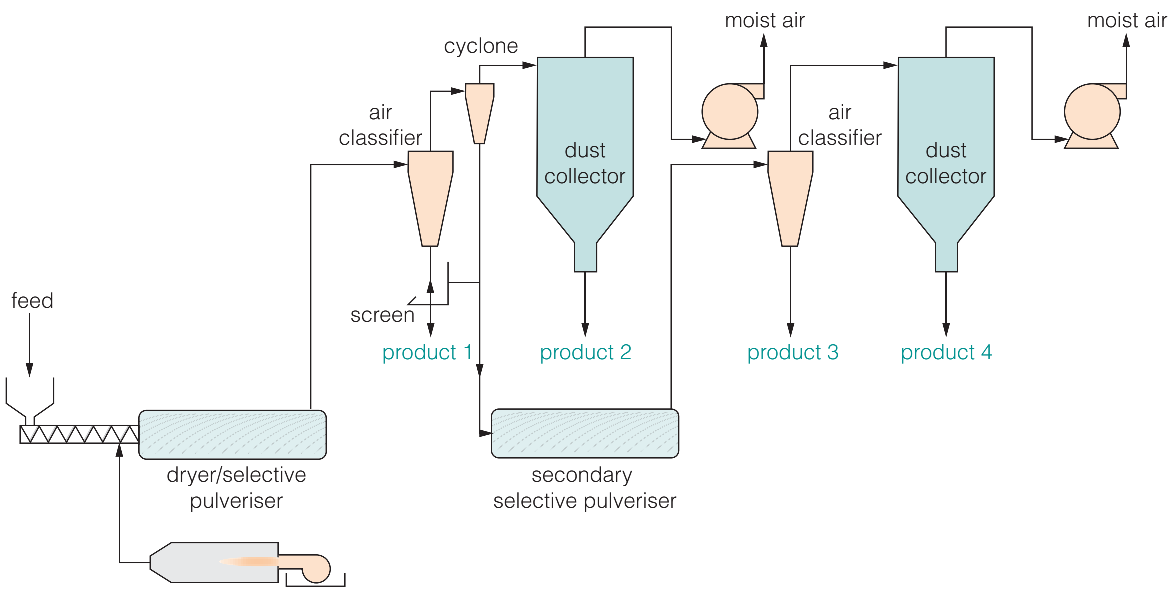

Figure 9 Differential Hardness Separation process for fine coal (Fiscor, 2010)

classification stage to produce a high silica material at the screen (Figure 9, Product 1). At the first dust collector a fine mixture of organic carbon and clays is produced (Figure 9, Product 2). Material passing the screen is mixed with the underflow from the de-dusting cyclone. This material is mainly organic coal but if a higher concentration is required it is passed to the second stage of selective pulverisation and air classification to give inorganic (Figure 9, Product 3) and organic concentrates (Figure 9, Product 4).

An alternative option avoiding the need to dewater fine coal is to incorporate it into a coal water mixture fuel and this is discussed in Section 5.3 1.

5.3 Manufactured fuel

5.3 1 Coal water mixtures

Coal water mixtures (CWM) form a subset of the more general category of coal liquid mixtures reviewed by Thambimuthu (1994). There are various reasons why CWM fuels are attractive.

Transporting fuel through pipelines can relieve the pressure on road and rail transport systems where 'dry' coal is transported. Liu's (2006) overview of coal pipeline technology includes two technologies of relevance:

- fine coal slurry: particles <2 mm, and most <0.2 mm, velocities > onset of turbulent flow (ensures particles are suspended) and <2 m/s (minimises pipeline abrasion);
- ultrafine slurry: particles <0.01 mm (typical of CWM fuels), addition of anti-coagulant permits flow rates in the laminar region and even flow stoppages.

An important attraction for utilisation of fine coal slurries is the potential for avoiding dewatering and its associated costs and complexities, and this led to the use of CWM from tailings in Russia fuelling industrial furnaces in the 1940s.

In addition to using CWM as the main or supplementary fuel feed for coal-fired boilers its use as a reburn fuel, SNCR aid (urea carrier) and mercury capture aid have been investigated at utility scale (Johnson and others, 2008). The trails of reburning yielded some degree of NOx reduction (ranging from 0% to 10%) but the amount of injection possible was limited by the level of CO generated which rose to unacceptable levels as the injection rate increased. The ability to use CWM as a carrier for other reagents is convenient and a synergy between the effects of the carbon and urea injected together was observed with a 30% enhancement in NOx reduction compared to urea alone. The addition of halogen salts to the slurry provided increased mercury capture in the ESP although CWM alone was not effective.

Cofiring tests of slurries of recovered coal fines with PC in a front wall fired unit with two rows of three burners produced significant NOx reduction when the upper row was cofired with CWS. Miller and others (1997) postulated that a degree of reburning was occurring in this arrangement.

Wibberley and others (2008) reviewed fine coal preparation technologies with potential for production of high-grade CWM fuels suitable for gas turbines (GT) or internal combustion engines (ICE). The technologies highlighted include:

- column flotation – considered the most promising for fine coal cleaning for CWM production;
- Kelsey Jig;
- Multi-Gravity Separator;
- Falcon Concentrator;
- Knelson Concentrator;
- ultrafine, dense medium systems for improved cleaning down to 30–40 µm; Carefree Coal and MicroMag.

Except for the column flotation types, which have been applied commercially for the recovery of both fresh and stored fines, most had limited market penetration or had not been commercialised.

The product quality requirements for GTs and ICEs are much more demanding in terms of ash content than is the case for industrial furnaces and boilers. So the potential for utilising fine coal residues in this application will depend upon their washability. Achieving the degree of cleaning required for tailings from coal washeries may be technically and financially challenging.

However, recent studies at CSIRO (Wibberley, 2011) have demonstrated that viable CWM fuels can be produced from a wide range of coal materials including fine coal preparation residues with high ash contents. These fuels are produced by micronisation of the coal material and separation by froth flotation. Low ash, high coal (50–60 wt%) fuels have been produced. Microfine low ash coal water mixtures for diesel engine fuel is not a new concept. However, developments in large-scale micronising mill technology and froth flotation of coal now mean that there is the potential to produce them at commercial scale even from low grade coal such as tailings. This would enable operators to take advantage of the efficiencies of direct injection coal engines (DICE) which are significantly higher that than for pulverised coal fired plant at much lower equipment costs.

Energy and Environmental Research Corporation and EnerTech tested fuel water mixtures composed of combinations of coal fines and carbonised RDF. Synergistic effects of blending these two fuel types included:

- reduced sulphur content;
- reduced ash content;
- increased volatile content;
- increased heating value;
- improved uniformity.

Pilot-scale combustion testing was successful, and the fuel showed promise as a potential reburn fuel (Zamansky, 1998). However, Enertech now only market their SlurryCarb™ process for processing biosolids.

5.3.2 Solid fuels

The simplest approach for fine coal deposits, providing that the quality meets customer requirements, is to dig it from a dried out impoundment and apply the minimum of breakage required to enable it to pass through a coal feed system (for example, passing it through a shredder).

Production of solid lump fuels is an established approach to improving the market acceptance of reject coal fines. Provided that sufficient strength and weather resistance is achieved the benefits can include improved handling, storage and utilisation characteristics. Couch (1998) discussed the main technologies in outline and Nunes (2009) considered them in the context of upgrading of low rank coals. They include:

- briquetting either; binderless or with a binder (for example roll press – typically ovoid);
- pelletisation by agglomeration (for example pan or disc pelletiser – typically spherical);
- pelletisation by extrusion (for example ring die pelletiser – typically cylindrical).

Alternative conformations have been tested to produce particular characteristics. For example Afri-Pal Spolka z o o market large cylindrical pellets (120 mm diameter, 100 mm length) in Poland. The briquettes are perforated with several longitudinal holes to give low-smoke combustion in domestic grates but according to World Mining Services (2010) they are also suited to the thermal power market. These are similar to the form of pellets, formed from local anthracite, that are marketed to domestic consumers in South Korea. Afri-Pal are manufacturing their product from a stock of approximately 0.5 Mt of coal in slimes residues remaining after closure of the Janina 2 mine over ten years ago.

Cass and others (1977) patented an extruder designed to dewater and pelletise fines in slurry. It involved passing the wet fines through ribbon flight screw conveyors with a co-flow of hot gas (usually air). The agglomerating mechanism was akin to that in pan/disk pelletisers combined with pressurised extrusion to provide the final product. Addition of a binder such as lignin sulphonate may be required in some cases. The technology does not appear to have been commercialised.

To improve handling characteristics (resistance to breakage), storage performance (resistance to moisture) and environmental characteristics (benign binders and briquettes with low or no smoke production) numerous binder combinations have been tested (Couch,1998). The application of heat during the briquetting process has also been investigated.

Co-processing coal fines with other materials may have other objectives beyond these basic physical/chemical characteristics and general economic viability of the process.

The addition of sorbent materials to fuels manufactured from fine coal has been investigated with a view to reduction of sulphur emissions (Jelks, 1987; Rapp, 1991) but the results were variable. Rapp

(1991) found that this approach was ineffective in stoker firing. The conditions in stoker fuel beds are likely to be unsuitable in terms of contact times, and possibly temperatures, for the necessary calcination and sulphation reactions required for effective sulphur capture. Conditions in fluidised bed combustors are more suitable with longer gas/solid contact times and lower temperatures.

The early work by CQ Inc included an investigation of a variety of potential binders and co-pelletising coal fines with various biomass or waste ingredients (Couch, 1998) including:
- paper sludge;
- sewage sludge;
- low-density polyethylene film;
- cardboard;
- sawdust;
- newsprint and waste office paper;
- grass and leaves.

Subsequently three preferred fuel formulations were identified (Akers and others, 2001):
- premium (anthracite fines + mixed plastics);
- medium cost/medium quality (coal fines + sewage sludge);
- low cost/low quality (coal fines + sawdust + asphalt emulsion).

Pilot testing was carried out using paper mill pulp with coal in a washery fine coal circuit (Akers and Shirey, 2005). Composite fuel with 5% paper sludge was successfully prepared and test fired in a 90 MW power plant.

Large amounts of fine coal and sawdust are deposited in Kentucky. Investigations into co-processing these two resources generally failed to identify synergistic benefits (Honacker, 2005). Investigations into co-briquetting spent mushroom compost with coal fines produced a similar result and it was concluded that there was no interaction between the compost fibres and the coal fines (Ryu and others, 2008). The addition of sawdust reduced the performance of dewatering filters, and efforts to minimise cost by using binders as flotation collectors were unsuccessful, although briquettes were produced and burned successfully at pilot scale (Honacker, 2005).

The main focus of these investigations was on how ‘other materials’ can be used to improve coal briquettes. However, from the biomass industry perspective the question of how the available biomass fuels can be presented to the market in an acceptable form has also prompted studies of co-processing with fine coal residues. The specific questions are:
1) How can biomass be economically transported to customers? This is largely an issue of high moisture content and low bulk density leading to relatively low energy content per unit volume.
2) How can it be stored, handled, and prepared for firing? There are several issues that are associated with these including the tendency of biomass to self-heat and its fibrous structure. To sell biomass into coal-fired boiler plants these technical issues need to be overcome with little or no investment from the customer.

Taulbee and others (2009) investigated co-briquetting of wood waste and fine coal residues using a hydraulic press to simulate pressures in a roll press type briquetting machine. The fine coal samples were thickener inlet material from two Kentucky coal preparation plants. Eleven sawdusts from different trees and preparation methods were included in the study.

From saw mills:
- White oak + some red oak (larger particle size from circular saw);
- Chestnut-oak – smaller particle size from bandsaw;
- Poplar.

Laboratory prepared from individual woods (chain saw):

Table 7 Binders used for sawdust/coal fines co-briquetting trials

Binder	Binder plus Lime
Asphalt-MS	✔
Asphalt-SS	✔
Black strap molasses	✔
Bleached softwood pulp	✔
Brewex	✔
Coal loading tar	✔
Cola syrup	✔
Corn starch unpolymerized	✔
Corn starch-polymerized	✔
Guar gum	✔
Hardwood pulp	✔
Lavabond	
Lime	
Paper sludge	✔
Peridur 300	✔
Peridur 330	✔
Phenolic resin-unheated	✔
Polybond	✔
Polybond 300G	✔
Promo-1	✔
Reax	✔
REAX-A	✔
REAX-N-DK	✔
REAX-N-EF	✔
RS-2	
RS-2 asphalt emulsion	✔
Slack wax (212)	✔
Sodium silicate	
Softwood pulp	✔
Spring wheat flour	
SS-1 asphalt emulsion	✔
Tall oil	✔
Western bentonite	
Wheat flour-high gluten	✔
Wheat flour-high starch	✔
Wheat flour-Walmart	✔
Wheat starch 6	✔
Wheat starch 7	✔

- Red oak;
- White oak;
- Poplar;
- Willow;
- Ash;
- Maple;
- Beech;
- Hickory.

The test matrix included over 50 potential binder combinations (*see* Table 7).

The effects of variations in amount of binder, and the period of maturation of the briquettes (fresh, one day and seven days) and water resistance were investigated with measurements of compressive strength. Drop shatter tests and attrition tests were also undertaken. It was found that:

- on an equivalent cost basis Guar gum, wheat starch, and Reax+lime were the best performing binders;
- binder concentration; sawdust concentration, particle size, and type; cure temperature; ash content had the greatest effect on briquette performance;
- moisture content, briquetting force, and briquetting dwell time had the least effect.

Overall most biomass materials are unlikely to interact with coal fines under conditions that are applied in briquetting equipment. So a binder must be used that is effective with both materials and which in itself provides strength and water resistance. Greenfields claim capability to briquette coal with biomasses to form robust water resistant briquettes however, the binder formulation is described as proprietary (Fiscor, 2010).

5.4 Coal conversion

The conversion of the organic coal material in coal production residues to a liquid (liquefaction) or gas (gasification) is an effective means of separating it from the inorganic mineral components.

5.4.1 Liquefaction

Coal-to-liquids processes including the effects of coal properties were reviewed by

Couch (2008). The processes are divided into four main types:

- carbonisation;
- mild gasification;
- direct liquefaction;
- indirect liquefaction.

The key question to consider in this context is whether these processes are able to accommodate feeds with the characteristics of the residues to be processed. Such factors as particle size, ash, moisture and sulphur content must be considered. The properties of recovered coal fines are: potentially high moisture, high ash and variable quality. Information about the resilience of liquefaction processes to variations in these fuel properties is limited because in general they have been developed for commercially-traded coal rather than coal production residues. Where catalytic processes are used high levels of sulphur present in some washery residues will limit catalyst selection options to those resistant to sulphur poisoning.

The initial process step for indirect processes is gasification. Conventional gasification technologies are covered in Section 5.4.2. WMPI PTY's, proposed 'Gilberton Coal-to-Clean Fuels and Power Co-Production Project' would use Shell gasification technology as the first stage of the production of liquid fuels from coal residues (NETL, 2008). However, it has not progressed to implementation and the US government eventually withdrew its $100 million support, although the company continues to lobby for government funding.

5.4.2 Conventional gasification technologies

There are three main categories of gasifier technology; moving or fixed bed, fluidised bed and entrained flow. Typically coal recovered from fine coal preparation residues has small particle sizes and relatively high ash contents. Comparing the typical constraints for the three types of equipment (Fernando, 2008) with these fuel characteristics identifies fluidised bed systems as the most likely to be applicable (*see* Table 8). If the ash contents are low or the material can be washed to below ~25% ash it may be suitable for entrained flow systems. Upgrading fines, by for example briquetting, would be required for use in moving bed systems.

In addition to these basic factors the coal composition will also affect suitability but in general this is a function of the parent coal rather the processes of separation, storage and recovery of fines. These factors are discussed in some detail by Fernando (2008).

Depending on the conditions and length of storage some degree of weathering will have occurred. The impact on reactivity also needs to be considered in assessing fuel suitability. Coal washing processes generally result in enhanced levels of sulphide minerals in washery residues compared to the parent coal. This will affect the amounts of sorbent needed to meet sulphur capture requirements.

Table 8 Gasification technology fuel flexibility

Gasifier type	Ash removal	Fuel size, mm	Ash content, %	Recovered fines, preparation
Moving/fixed bed	Dry	5-80	no limit	Size upgrade
	Slag	5-80	<25	Size upgrade
Fluidised bed	Dry	<6	no limit	None
	Agglomerate	<6	no limit	None
Entrained flow	Slag	<0.1	<25	Rewashing

5.4.3 Gasification drying technologies

As with all thermal processes the moisture content of the fuel affects temperatures in the plant. This must be considered in assessing the suitability of the fuel for a particular plant. Entrained flow gasifiers can accept coal slurry feeds. An alternative is to dry the material and some designs have been developed to achieve this within circulating fludised bed gasifier systems. Charbonnage de France (CdF) developed a system specifically for fine coal preparation residues or 'schlamms'. Feeding the wet fines into the fines recycle system, either to a cyclone inlet or into a recycle line, allows residual heat in the flue gas to be used without impacting directly on the gasifier operation (Delessard and others, 1985). The general arrangement of the proposed system is illustrated in Figure 10.

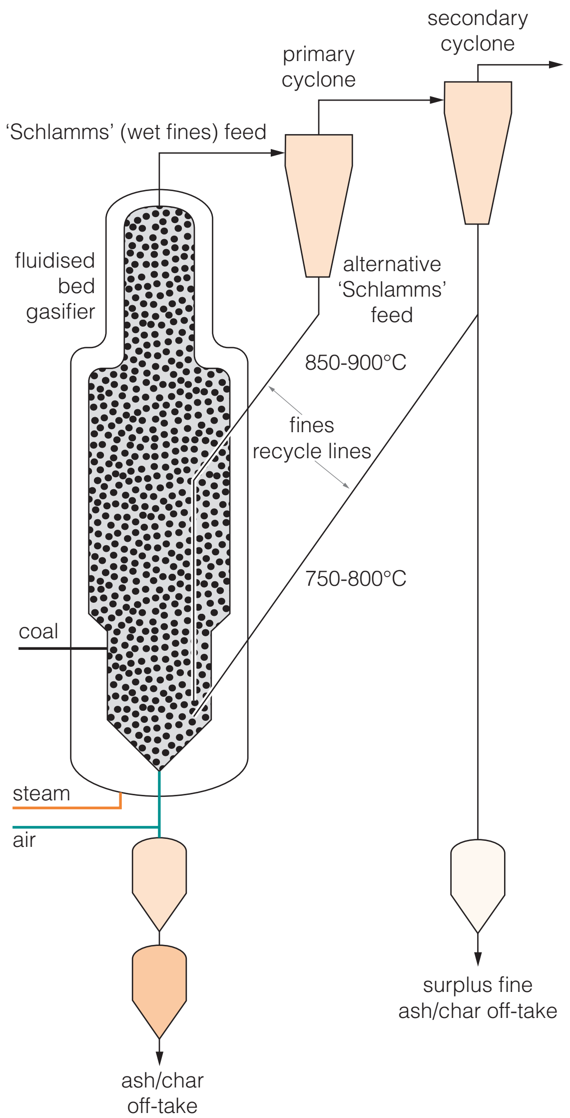

Figure 10 'Schlamms' gasification technology developed by Charbonnages de France (Delessard and others, 1985)

The CdF technology has some similarities to the Integrated Drying and Gasification Combined Cycle (IDGCC) process developed for high moisture, low ash Australian brown coals (Fernando, 2008). In that case the brown coal is the only fuel and is introduced to the system in the line between the primary and secondary cyclone. However, work has not commenced on construction of the IDGCC plant proposed for Victoria, Australia and so this type of drying circuit has yet to be demonstrated at full scale.

5.4.4 Plasma gasification

What is 'plasma'?

Plasma gas is a high temperature fluid containing charged gas species which results in behaviour significantly different from other fluids. It is sometimes referred to as the 4th state of matter and Eliezer and Eliezer (2001) provided an accessible overview of plasma physics.

Thermal plasmas are generated by electric (AC or DC) arc discharge (5000°C to 7000°C) and have numerous applications. Devices are divided into two principal categories (Figure 11). Where both electrodes (anode and cathode) are incorporated into a plasma torch assembly the thermal plasma is referred to as 'non-transferred'. Where the plasma torch incorporates only the cathode and the discharge occurs to some other part of the reactor the plasma is termed 'transferred'. Transferred thermal plasmas are generated in conventional electric arc furnaces. Plasmas can also be induced using radio frequency energy, so called electrodeless plasmas. Hybrid versions including both DC discharge torches and RF elements have also been developed (Brecher and others, 1991). Matveev and Serbin (2007) modelled a hybrid design physically and mathematically and found that the hybrid approach brought significant increases in the plasma generation efficiency.

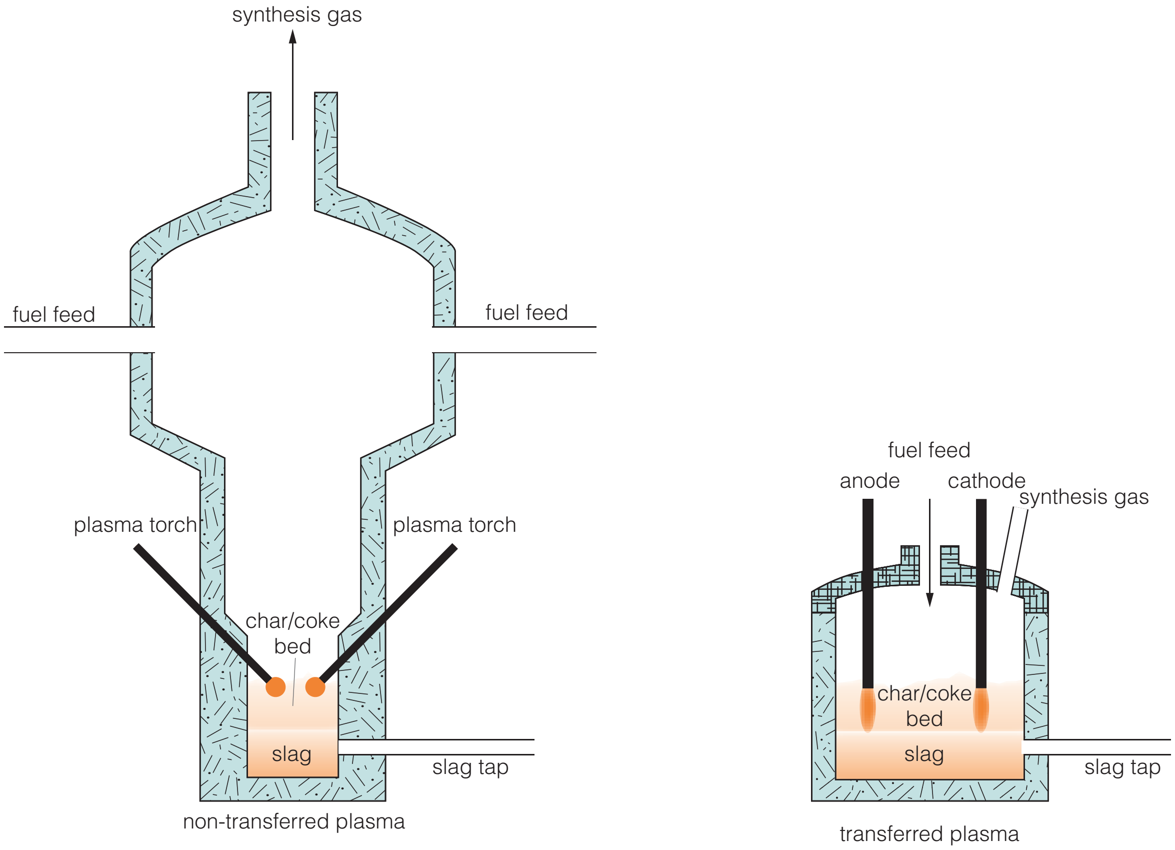

Figure 11 General arrangement of gasification reactors using non-transferred and transferred plasmas (Westinghouse Plasma Corporation, 2002; Solena Group, nd; Do and Leatherman, 2006; Carabin and Gagon, 2007; Plasma Waste Recycling, nd)

Thermal plasmas can be used to provide the temperatures required for a form of slagging gasification of a wide range of materials including coal production residues.

PyroGenesis Inc 'Plasma Gasification Vitrification of Ash' (PGVA) process is an example of a use of a transferred thermal plasma (Carabin and Gagon, 2007). Other plasma gasification systems are based on non-transferred plasmas making use of sophisticated plasma torches (Westinghouse Plasma Corporation, 2002, Solena Group, nd, GESI, nd). The use of hybrid torches has also been proposed as offering much longer torch life.

Plasma gasification can be embodied in plant with relatively small footprints and so offer a transportable solution (Matveev and Serbin, 2007). This is appropriate for recovery of coal preparation residues where the scale of the resource, although significant, may not be sufficient to justify investment in permanent plant.

Various companies market plasma gasification technology for waste treatment and biomass to energy conversion – for example Solena Group (www.solenagroup.com/science) and Europlasma (http://www.europlasma.com/). Benefits of the technology, particularly for waste processing, are the encapsulation of inorganic species in a dense unreactive glassy slag and energy recovery through the generation of a synthesis gas (*see* Figure 12)

Plasma gasification or plasma assisted gasification has features in common with a moving bed slagging gasifier. Fuel is fed over the bed, organic material is gasified and inorganics melt into the molten slag at the bottom of the vessel from where it is tapped. However, the same particle size constraints of conventional moving beds do not apply. Laboratory studies of the performance of

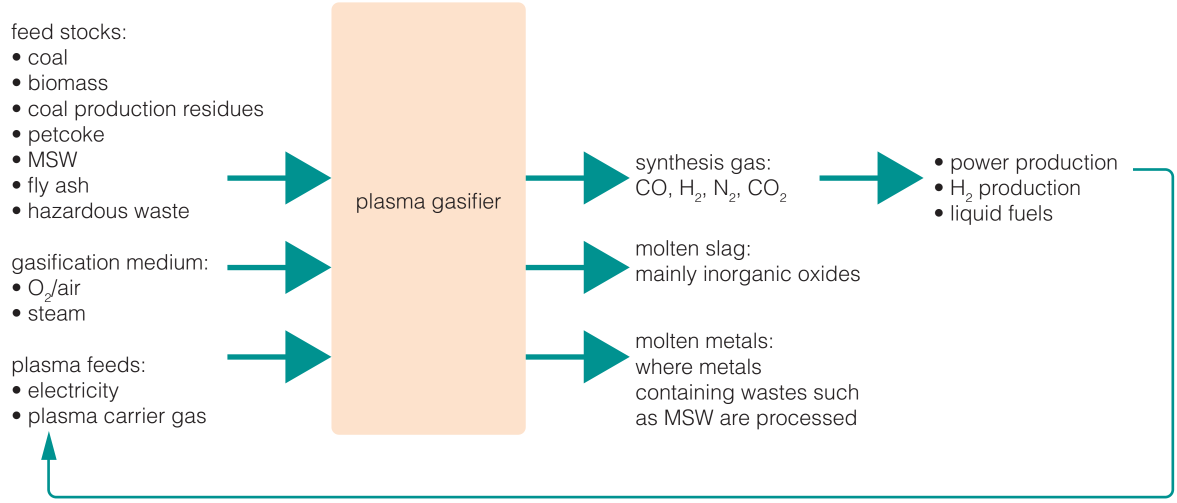

Figure 12 Generalised plasma gasification process scheme

plasma gasification of a bituminous coal and a petroleum coke used samples with mean particle sizes of 75 µm and 150 µm respectively (Lavrichshev and others, 2008). Carabin and Gagon (2007) demonstrated the potential for processing fly ash from combustion plant with poor carbon burnout which is analogous to fine, high ash, low volatile matter content coal production residues, such as anthracite culm.

Efforts to increase overall efficiency of gasification based power generation systems have focused on development of combined cycles. Global Environmental Solutions Inc (GESI, nd) and the Solena Group market an integrated plasma gasification combined cycle (IPGCC) and Alter NRG also considered this option. However, an independent review of the Alter NRG / Westinghouse Plasma Corp embodiment of plasma gasification concluded that this would have been a 'step too far' given the state of the technology at the time (Juniper Consultancy Services, 2008).

Several companies have marketed technologies for processing of coal preparation residues including GESI (GESI, nd), the Solena Group (Solena Group, nd) and Westinghouse Plasma Corp (currently owned by Alter NRG) (Westinghouse Plasma Corporation, 2002). However, no plants using this technology have been built to process coal production residues. The main target markets are currently dealing with wastes that have zero or negative value, and neither Alter NRG nor PyroGenesis are currently targeting coal production residues as a market opportunity (Hall, 2011, Carabin, 2011). NRG Energy had for several years been seeking to retrofit its now-closed coal-fired power plant at Somerset, MA, USA with plasma gasification reactors using Alter NRG technology. This would have used coal rather than production residues but in February 2011 they abandoned this plan.

5.5 Combustion

5.5.1 Conventional technologies

There are three main categories of combustion plant, analogous with those for gasification (Section 5.4.2):

- fixed or moving beds – ranging from domestic open grates to large industrial stokers, with a wide range of stoking mechanisms available;
- fluidised bed combustors;
- entrained flow combustors – pulverised coal (PC) fired boilers and cyclone combustors fall into this class.

Table 9 Basic coal specification for combustion equipment types

Combustor type	Ash removal	Fuel size, mm	Ash content, %	Recovered fines, preparation to meet specification
Moving/fixed bed	Dry	20–30	5–20*	Size upgrade
Fluidised bed	Dry	2–6†	no limit	None
Entrained flow	Dry	<0.4 & 70%<0,075‡	typically <20	Rewashing
			exceptionally <40	None
	Slag (cyclone)	95%<4.75*	<25*	Rewashing

* Adams and others, 2007
† Wu, 2003
‡ Wu, 2005

Table 9 gives a summary of the basic coal specifications for the various types of combustion technology and a summary of essential actions to enable recovered fines to meet these requirements.

Coal combustion technologies were extensively overviewed by Adams and others (2007). In this section they are discussed solely in the context of their ability to accommodate fine coal production residues.

Moving/fixed bed – stokers

There are three main types of stoker – underfed, overfed, and spreaders. All rely on forming a bed of material on a relatively coarse grating and so lump fuels are used. It is not possible to use fuel with small particle sizes because it either falls through the grate or is blown off it by the combustion air and combustion cannot be sustained. Therefore, fine materials need to be upgraded in size to provide the necessary fuel characteristics (*see* Section 5.3.2).

Fluidised bed combustors

There are two main types of fluidisation regime used in combustors – bubbling and circulating. These may be operated either at atmospheric pressure or at elevated pressure. Wu (2003) and Wilhelm and others (2002) have provided technology overviews of fluidised bed combustion (FBC).

FBC is commonly applied to the recovery of energy from low grade fuels (high ash, high sulphur, high moisture) such as wastes from coal mining and washing. Table 10 compares the performance of circulating fluidised bed combustion (CFBC) plants firing a range of fuels.

Bubbling fluidised bed combustion (BFBC) plants are generally smaller plants of <75 MW although some have been up to 120 MW, whereas CFBC were up to ~320 MW (Wilhelm and others, 2002). However, the proven scale of CFBC has increased significantly with several thousand hours of successful operation of the first 450 MW unit at Łagisza in Poland. On this basis the supplier of the plant is now offering supercritical CFBC for bituminous coal of up to 800 MWe (Hotta and others, 2010).

Opting for CFBC for the Łagisza plant provided wide fuel flexibility (*see* Table 11). The main fuel is bituminous coal from ten local mines with a range of coal properties. The main secondary fuel is coal slurry, which can be burnt either wet (to provide up to 30% of the heat input) or dry (to provide up to 50% of the heat input). In addition biomass can be accommodated at up to 10% of the fuel input (Venäläinen and Psik, 2004)

Table 10 Representative CFB Boiler efficiencies and plant heat rates for various fuels* (Wilhelm and others, 2002)

Fuel	Boiler efficiency, (HHV), %	Average gross heat rate, kJ/kWh	Auxiliary power, % of Gross‡	Average net heat rate, kJ/kWh
Bituminous coals	87–88†	9,040	9.0	9,940
Petroleum coke	89–90†	8,840	9.0	9,710
PRB subbituminous coal	84–86†	9,310	8.5	10,180
Lignite	82–85‡	9,470	9.0–11.0	10,530
Gob (60% ash)	85–87‡	9,200	11.0–13.5	10,360
Culm (60% ash)	83–85‡	9,420	11.0–15.5	10,730

* Basis:
Unit sizes above 200 MW (net)
20% excess air, except in the case of culm with 25% excess air
90–94% SO_2 capture, except in case of PRB coal which is 70–74%
Steam turbine generator heat rate = 8,018kJ/kWh with electric motor driven boiler feedwater pumps and 85 mbar condenser back pressure

† Based on discussions with Foster Wheeler

‡ SFA Pacific estimates, from SFA Pacific Inc

Table 11 Lagisza fuel specification (Venäläinen and Psik, 2004)

	Bituminous coal		Coal slurry
	Design fuel	Range	Range
LHV, % ar	20	18-23	7-17
Moisture, %	12	6-23	27-45
Ash, % ar	23	10-25	28-65
Sulphur, % ar	1.4	0.6-1.4	0.6-1.6
Chlorine, % db	<0.4	<0.4	<0.4

Table 12 Units firing ‘waste coal’ fuels, by technology (IEA CCC, 2011)

Unit type	Number of units	Rated capacity, MW
CFBC	83	15,390
CYCLONE	1	173
FBC	2	133
PC	19	7,742
PCFBC	1	100
STOKER	2	126
Unknown	36	4,522
Total	144	28,185

CFBC is a popular solution to combustion of low grade coals and particularly for colliery wastes. It is resilient to operation with high ash and moisture fuels. Coarse coal preparation residues are often rich in pyrite and so the ability to capture sulphur oxides through addition of sorbents to the bed is an important feature.

The IEA CCC Coal Power database includes many thermal power plant units that report some form of ‘waste coal’ amongst their fuels. The breakdown by boiler technology is shown in Table 12. CFBC is the most common technology mainly because of the large number of gangue-fired units installed in recent years in China (*see* Table 13).

Table 13 Units firing 'waste coal' fuels, by country (IEA CCC, 2011)

Country	Number of units	Rated capacity, MW
Australia	1	150
Brazil	2	440
Canada	1	50
China	95	15,236
France	3	975
India	1	75
Poland	1	136
Spain	1	50
Ukraine	1	210
USA	36	10,414
Vietnam	2	450
Total	144	28,185

Entrained flow – pulverised coal

The predominant technology for coal combustion is as pulverised coal combustion which enters the combustion chamber entrained in a flow of air. The fundamental combustion processes are set out by Wu (2005).

Fine grinding of fuel is required so the fineness of coal preparation residues can be beneficial. A proportion of fines from preparation plants are routinely back blended into power plant fuels. Table 12 suggests that very few of the many hundreds of PC fired units installed worldwide burn recovered fines. However, it is likely that many more take at least some either blended with their normal coal feed or separately from closed impoundments. In the latter case the material may be simply dug out, delivered and passed through a shredder prior to entering the coal feed.

The level of recovered material that a particular unit can tolerate will depend on its design parameters but blending with suitable coal enables plant fuel specifications to be met. However, coal feeding, preparation and firing systems are designed for 'dry' coal. The incorporation of 'wet' fines can lead to feeding problems, and wet/winter conditions tend to increase problems. Reducing or stopping addition of recovered fines is the usual way to respond to such conditions.

5.5.2 Hybrid coal gas turbine

Destruction of methane in mine ventilation air (VAM) is challenging as concentrations are variable and too low to provide the sole fuel for a combustion system. The established technology for dealing with low concentration combustible gaseous emissions is the thermal oxidiser and with these the usual support fuel is natural gas. However this is a costly option and in the context of coal mining there are low-cost alternative fuels available. Various systems have been developed to address this and these have included the use of coal mine methane (CMM) (Schloss, 2006) and of coal production residues as the support fuels. This latter developed at CSIRO, Australia is known as the Hybrid Coal Gas Turbine (HCGT) (CSIRO, 2002).

The system developed by CSIRO comprised a rotary kiln coupled via a specially designed heat exchanger to a gas turbine. Methane in ventilation air is burnt in the kiln with coarse (6–8 mm) coal preparation residues acting as a low cost support fuel (*see* Figure 13). The support fuel is also used to smooth out the energy input as the concentration of methane in the ventilation air fluctuates (Glynn and others, 2005).

Although, this format has an elegant simplicity, avoiding the complexities associated with operation of steam systems, an alternative approach was taken by CSIRO's partner Liquatech as they sought to commercialise the technology. In this case the heat from the kiln is captured using a heat recovery steam generator (HRSG) coupled to a conventional steam turbogenerator. Currently EESTECH are marketing the steam-based system (*see* Figure 14). This configuration has been adopted as the sub-systems (HRSG and steam turbine cycle) can be considered as proven technology whereas the hot gas system relied on specially-designed heat exchangers.

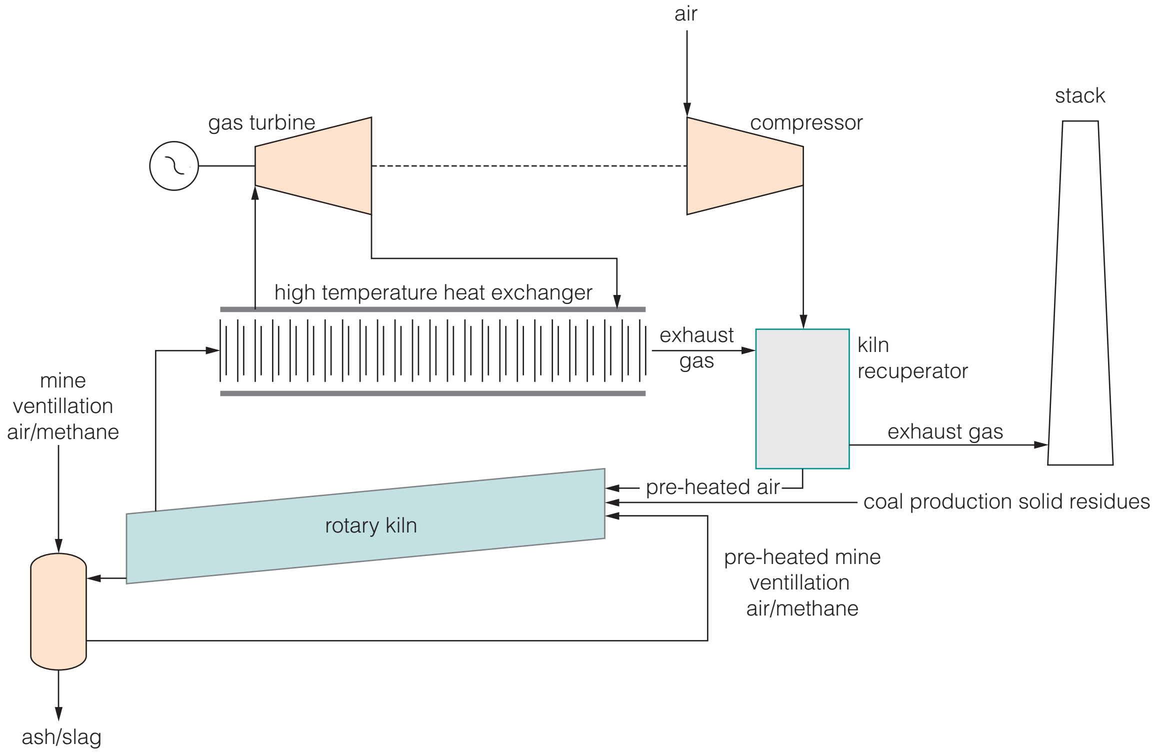

Figure 13 Schematic of the arrangement of the HCGT developed by CSIRO which makes use of a gas turbine and the Brayton cycle (Glynn and others, 2008)

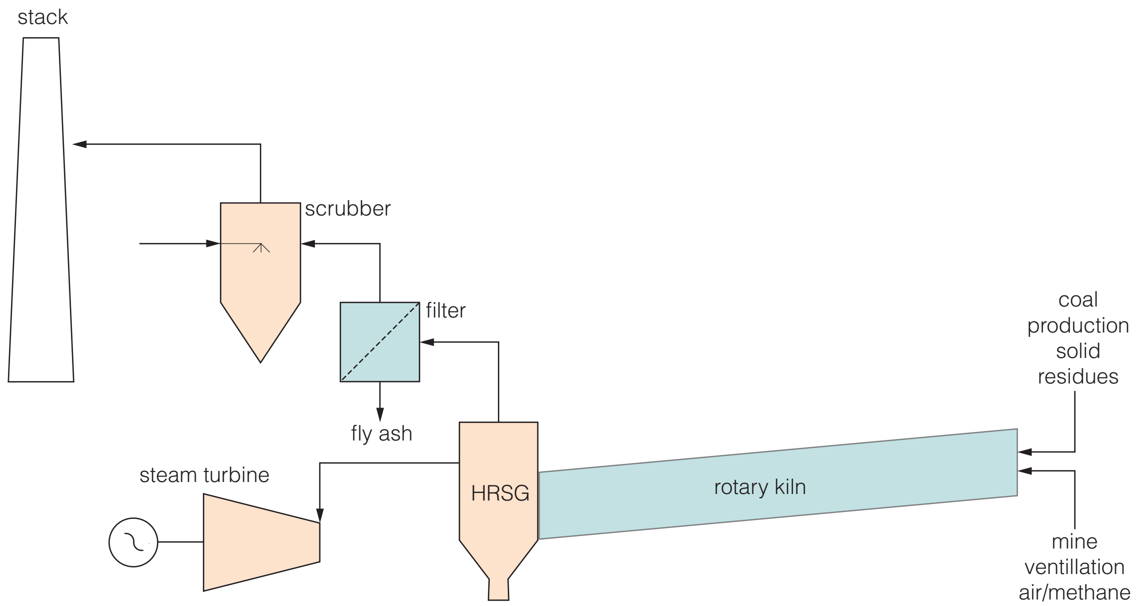

Figure 14 Schematic of the arrangement offered by EESTECH which makes use of a conventional steam cycle

Early attempts by Liquatech / CSIRO to develop projects foundered, as lenders were unwilling to bear any financial risk. Energy Daily (2008) reported a joint venture with Aryan Clean Coal Technologies to install three 10 MW units over the coming five years as well as reports of agreements in China for a 30 MW plant to be constructed in Fuxin. These plants do not appear to be built yet. Thus the technology remains unproven at industrial scale. However, extensive pilot-scale testing was carried out at CSIRO and for the steam cycle type unit all the key component parts are commercially available (rotary kiln, heat recovery steam generator and steam turbine) which reduces the risk for any user adopting this technology.

6 Country summaries

The global estimate presented in Section 2.5 was based on a simple model using estimated average tailings rates and total production figures for the world's regions. Published overall estimates of amounts of coal washery residues, either stockpiled or impounded, are only available for a few countries and are rarely supported by any description of the methodology used to develop them. In some cases it is unclear whether the estimate relates to organic coal only, all solids or solids + liquid (slurry) and what sources are included; spoil, coarse cleaning wastes, fine cleaning wastes or some combination of these. In some locations the coal mining history indicates that deposits are likely to exist but records of deposits are sparse or not readily accessible. Records in registries/inventories are often in terms of volume or area covered.

In various countries there are or have been specific activities either deliberately to exploit the opportunity that coal production residues present or at least to take advantage of it in the process of dealing with these materials when driven by other concerns (environmental, health and safety).

The situation varies between countries and this chapter presents country profiles based on available information of stocks, production and utilisation of coal preparation residues. The absence of information should not be interpreted as absence of coal production residues.

6.1 The Americas

Coal mining in North America is extensive with a long history, and coal preparation techniques have become highly developed. In Central and South America coal preparation is less widely applied than in the North.

6.1.1 Brazil

From 1981 to 2008 Brazil's annual coal production was between 4.6 and 7.7 Mt/y with total production in the period of 165.6 Mt (BP, 2010). Around 3.5 Mt/y of coal waste are dumped in Santa Catarina State (Silva and others, 2010). In Brazil there is particular concern over potential leaching of metals from coal tailings, and studies have been undertaken to investigate their environmental impact (Amaral Filho and others, 2010). Kray and others (2008) investigated the impact of spreading industrial residues, and this included coal production residues. The compositions of the residues used for the studies are shown in Table 14.

Amaral Filho and others (2010) investigated the contents of an estimated 11 Mt deposit of coal tailings in an impoundment at Verdinho, Forquilhinha County, SC, Brazil. The impoundment takes coarse (–50.8 mm + 2.0 mm) and fine (–2.0 mm + 1.0 mm) washery rejects plus sludge from settlement ponds. Borehole samples were extracted and size and density fractions analysed to identify potential uses for the materials if secondary processing is adopted rather than the current practice of dumping in the impoundment (*see* Table 15).

The construction of a 400 MW CFBC based power station in the south of Santa Caterina state will reduce the amounts of residues as it will take local ROM coal and some recovered pond fines. It will accept fuels of up to 67% ash and 3.2% sulphur and it is planned that this station will commence operating in 2012.

Ruiz and Chaves (2009) investigated the scope for applying flotation technologies to cleaning coal tailings from Brazilian coal production. The investigations demonstrated that from a sample of fines

Table 15 Summary of the properties of residues from the Verdinho impoundment

Relative density	Size, mm	Sulphur, %	Ash, %	Mass, %	Possible products
<2.3	2.0–50.8	2.3	60.8	8.4	Energetic coal
	0.1–2.0	3.3	60.5	6.8	
2.3–2.8	2.0–50.8	1.8	87.7	50.8	Construction; ceramic; stonemeal; backfill
	0.1–2.0	2.8	87.7	5.8	
>2.8	2.0–50.8	38	66.4	7.8	Sulphuric acid, ferric coagulant, ferrous sulphide, ferric oxide nanoparticles; inorganic pigments
	0.1–2.0	17.8	76.2	1.4	
n/a	<0.1	3.1	67.6	19	Energetic coal

Table 14 Analysis of coal mine refuse used in horticultural investigations (Kray and others 2008)

	Coal mine refuse	
	I	II
Solid content,g/kg	905	925
pH (water)	7.1	7
Organic carbon, g/kg, db	242.9	183.8
Nitrogen, g/kg, db	3.6	2.3
Phosphorus, g/kg, db	0.3	0.3
Potassium, g/kg, db	0.07	0.06
Calcium, g/kg, db	18.6	19.0
Magnesium, g/kg, db	0.7	0.7
Sulphur, g/kg, db	83.6	85.0
Copper, mg/kg, db	23	25
Zinc, mg/kg, db	207	126
Manganese, mg/kg, db	541	194
Chromium, mg/kg, db	<0.1	0.3
Cadmium, mg/kg, db	13.02	12.85
Nickel, mg/kg, db	19.8	19.2

(63% ultrafine is less than 0.014 mm) recovered from an impoundment with a composition of 56% ash, 1.2% sulphur and calorific value of 5800 kJ/kg, flotation enabled 74% of the organic coal material to be recovered resulting in a product with 7.3% ash and a calorific value of 6116 kJ/kg to be recovered.

6.1.2 Canada

Canada is a significant producer of metallurgical coals and exporter of thermal coals and washes coal for these markets. Between 1969 and 1992 Japanese demand for metallurgical coal and growth in thermal coal exports led to the construction of 13 new coal preparation plants.

Coal production in Canada is from Saskatchewan (SK), Alberta (AB), British Columbia (BC), New Brunswick (NB) and Nova Scotia (NS). It has been between 60 and 80 Mt/y over the past 20 years with a total of about 687 Mt of bituminous coals produced. Statistics from The Coal Association of Canada (nd) show a decreasing trend since 1996 and shift in the balance between bituminous and subbituminous and lignite with the latter overtaking the former in 2000 (*see* Figure 15). Their records indicate coal preparation plants at 14 out of 16 bituminous coal mines. Only the mines in NB and NS are without plants and their production levels are low (estimated to be <0.2 Mt/y although they are not published). The total preparation plant capacity is just over 47 Mt/y enabling all bituminous coal produced to be washed apart from that from NB and NS.

Concerns from both environmental and industrial interest groups over abandoned and orphaned mines during the late 1990s prompted the establishment in 2002 of the National Orphaned/Abandoned Mines Initiative (NOAMI) (http://www.abandoned-mines.org). The initiative encompasses all types of mine and has five main task areas, one of which relates to information gathering and inventorying.

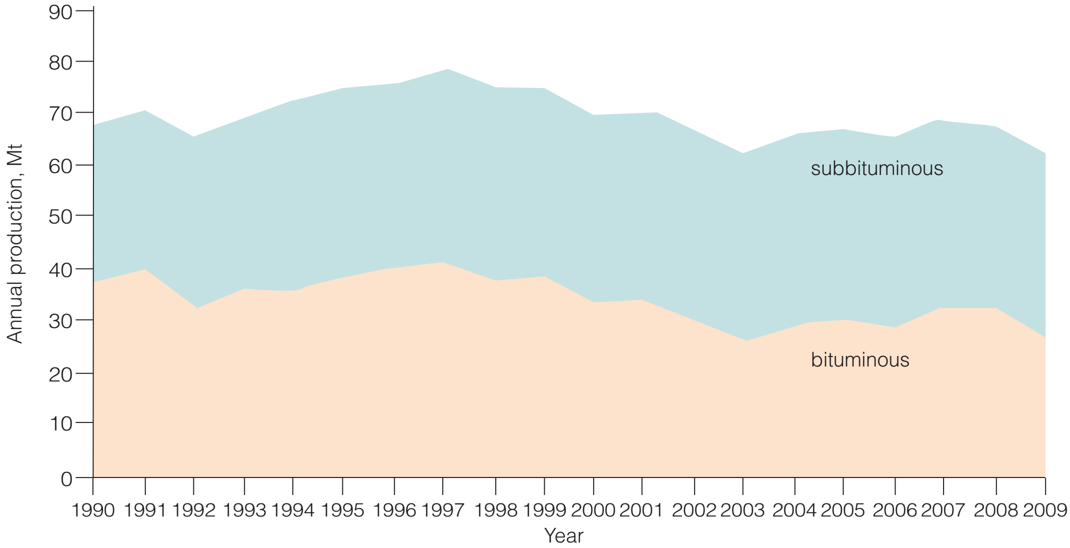

Figure 15 Canadian coal production trend (The Coal Association of Canada, nd)

The mandate for this task is: 'To develop capacity for a national inventory of active, closed and orphaned and abandoned mine sites based on compatible inventories in each province and territory, and to include agreed-upon national definitions and terminology as applied to orphaned and abandoned mine sites.' (NOAMI, 2009).

Cal Data were commissioned by NOAMI to carry out background research for development of the inventory database (Cal Data Ltd, 2005). They concluded that all the territories/provinces had at least two relevant databases which would need to be seamlessly incorporated into the proposed national database.

6.1.3 Colombia

Around 5% of Colombian coal production is washed. However, as the total production was 73.5 Mt in 2008 (BP, 2010) there is scope for large amounts of fine tailings to be produced. No official estimate of the amounts of coal preparation residues was found but assuming 5% is typical of the proportion of material washed since available production records started in 1981, and that about 20% of material is rejected in washeries, a residue accumulation of over 8 Mt is feasible.

6.1.4 USA

The long history and large scale of the US coal mining industry has produced a commensurate legacy of coal production residues (mining spoil, overburden, dry screened fines and washery residues). The EIA (2006) provided a summary history of the US coal industry.

All forms of mining have some impact on the land, most extensive from surface mining. Although some states had legislation requiring some degree of restoration of sites as early as the 1930s it was the passing of the 1977 Surface Mining Control and Reclamation Act (SMCRA) that introduced strict regulation of surface mining. Although this law was primarily prompted by, and deals with, surface mining activities it also affects the recovery of coal mining and preparation residues deposited on the surface. Various US inventory/registry systems are identified in Section 5.1.1.

US Census Bureau, Economic Census (http://www.census.gov/econ/) data for coal mining is extensive. Table 16 presents a summary of the numbers of coal mines (underground and surface) and coal preparation plants either at the mine or at a separate location.

Table 16 US coal (anthracite, bituminous, subbituminous and lignite) numbers of mines and preparation plants (US Census Bureau, nd)				
Year	1992	1997	2002	2007
All mines	2545	1507	1174	660
Mines with coal preparation plants	568	375	396	388
Separate coal preparation plants	89	75	42	25

Table 17 US coal processing statistics, Mt (including bituminous, subbituminous and lignite) (US Census Bureau, nd)				
Year	1992	1997	2002	2007
ROM – Not processed	13.5	7.1	13.2	18.1
ROM – Crushed/screened or sized	420.3	499.0	550.5	517.7
ROM – Washed	637.8	644.7	415.7	572.0
Percentage washed	**60**	**56**	**42**	**52**
Product – Crushed/screened or sized	412.4	498.5	546.1	426.4
Product – Washed	407.6	402.4	303.2	427.9
Residue – Crushed/screened or sized	7.9	0.5	4.4	91.4
Residue – Washed	230.2	242.3	112.5	144.1
Washing residue, %	**36**	**38**	**27**	**25**
Total ROM	1071.6	1150.8	979.3	1107.8
Total residue	238.0	242.8	116.8	235.4
Residue, %	**22**	**21**	**12**	**21**

Table 18 Number of underground slurry injection sites (GEO22, 2009)	
State	Active count
West Virginia	13
Kentucky	14
Pennsylvania	2
Ohio	2
Maryland	1
Virginia	2
Tennesse	0
Indiania	1
Illonois	3
Alabama	5
Montana	1

The data from the Economic Censuses of 1992, 1997, 2002 and 2007 show that most bituminous coal from underground mines was processed in some way, although a significant minority was sized only. The situation is reversed for surface-mined coal and 20% to 30% washed, 65% to 80% crushed/screened/ sized. Table 17 summarises the preparation data and estimates of coal preparation residue generation rates.

Underground injection of tailings slurry is practised in several states to some extent though predominantly in West Virginia and Kentucky (*see* Table 18). It is has been estimated that about 15% of the coal slurry produced annually in the USA is disposed of in this way (Ducatman and others, 2010) leading to the loss of any potentially useable organic content.

The rate of fine coal discard to impoundments

Table 19 US coal production (Mt) by mining type (IDNR, 2010)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
Auger	6.61	5.11	4.42	3.86	5.75	7.80	8.76	8.69	7.51	5.53	5.20	69.23
Culm bank/Refuse pile	3.52	1.15	0.35	0.38	0.43	0.31	0.35	0.77	0.53	1.57	1.60	10.96
Dredge	0.61	0.67	0.41	0.52	0.46	0.32	0.34	0.28	0.74	0.86	1.01	6.22
Strip, Quarry, Open pit	628.39	671.77	663.03	647.39	668.81	685.40	719.70	711.34	730.41	665.86	671.38	7,463.49
Underground	338.95	344.67	323.96	319.77	332.50	334.40	325.67	319.14	324.45	301.24	305.84	3,570.61
Total	978.07	1,023.37	992.17	971.92	1,007.95	1,028.24	1,054.83	1,040.21	1,063.65	975.07	985.03	11,120.51

has been estimated at 70–90 Mt/y (Greb and others 2006). This is around 30 Mt/y lower than the residue rates estimated from the Economic Census data and may be indicative of the amount of material that is not impounded.

A 1991 tally covered only the 700 impoundments in AMLIS but concluded the overall fines content was 2 Gt (Kent and Risch, 2006). An estimate for 1994 arrived at a generation rate of 109 Mt/y of residues from 600 coal preparation plants in 21 coal producing states (US EPA, 2011a). Shirey and Jacques (1996) refer to studies estimating the loss of fine coal as 50 Mt/y with 2 Gt of recoverable fines in old tailings impoundments. Zamansky (1998) gave similar values and refers to more than 400 permitted waste fines impoundments and 3000 to 5000 abandoned waste fines impoundments.

Recovery of coal from production residues is a recorded element of US coal production but constitute an insignificant amount compared to the rate at which the residues are generated (Table 19).

Estimates of overall amounts of coal production residues stocked in the USA are referred to in numerous publications. Overall published estimates range from 0.5 to 3 Gt of deposits of coal preparation residues. Generally the methodology and point in time to which the estimate relates are not stated explicitly. However, it appears that overall estimates of around 2 Gt date from the mid-1980s. Taking the middle of the range of estimated fine coal discards to impoundments (70–90 Mt/y) current stocks of 4 Gt is a credible estimate.

The US Federal mining regulation system has presented various barriers to secondary coal recovery from deposits of coal production residues and individually the affected states have sought to enable coal recovery operators to overcome these as the removal of this material is widely viewed as beneficial (LRC, 1985).

Numerous companies in the USA are or have been involved in reclamation of coal production residues and a few examples follow:

- IBCS Mining (www.ibcsmining.com) have five sites in West Virginia and Kentucky. The site origins range from 1905 to 1968 and each contains between 21% and 48% of 'high quality steam and metallurgical coal'. They estimated the total area of these sites to be 600 acres

(~240 ha) and that there were around 40 Mt of material to process, with the expectation of recovering around 14 Mt of coal. The resources are a mix of heaps and dried-out impoundments. The pond fines are considered of sufficient quality to require no processing beyond extraction using mobile plant;

- Beard Technologies Inc were active in reclamation of coal production residues until 30 April 2010 when their parent company withdrew from all their coal operations (www.sludgesafety.org/news/2006/11_02b.html). Beard had a 'proprietary coal reclamation technology' for the recovery of coal fines from the slurry impoundments. They estimated that 10–15% of the coal that has been mined over more than the past 100 years resides in such impoundments. One project with an estimate of more than 2 Mt of recoverable coal was the Smith Branch Coal Slurry Impoundment near the Pinnacle mine complex. A paste thickener was installed to stabilise waste returned to the pond and the recovered coal was sold with metallurgical coal from the Pinnacle mine. (Kent and Risch, 2006);
- Targe Energy Reclamation, LLC (www.targe-energy.com) operates several sites in Northern and Central Appalachia where they re-mine coal production residues. They operate a fines recovery project at CONSOL's closed Turkey Gap impoundment in Mercer County (Kent and Risch, 2006);
- R & S Resource Recovery Inc (www.randsrecovery.com/index-old.htm) have recovered coal and coke products from abandoned coke oven sites and abandoned coal tailings impoundments;
- Headwaters Energy Services, Covol Engineered Fuels (www.covol.com/coalCleaning.asp) own and operate eleven coal cleaning plants, which recover carbon from coal production residues that are stored in piles and impoundments from previous coal mining/ preparation operations. Their binder based pelletisation process was used at several sites in West Virginia including McDowell, Raleigh and Upshur Counties to process coal fines and produce pellets that could be burnt in conventional power plants. However, a tie-in to federal tax incentives that expired in 2007 means that most of these operations have closed or shrunk substantially (Kent and Risch, 2006);
- Deepgreen West Virginia operates a dredging operation in the impoundment established in the 1890s at the former Pageton Preparation plant in McDowell County. A 2003 estimate found about 1.2 Mt of useable coal reserves in the impoundment. The recovered coal is blended with fresh coal and burnt in conventional power plants (Kent and Risch, 2006);
- United Coal Company has been involved in a Department of Energy demonstration project in Logan County since at least 1989. The project plans were to produce dry low ash, low sulphur coal from dredged fines (Kent and Risch, 2006);

The IEA Coal Power database shows 40 coal-fired power plant units in the USA in which 'waste coal' forms part or all of their fuel supply. From US national statistical records US EPA (2011a) identified fewer power plants burning waste coal as primary (18) or secondary (13 with bituminous coal as primary) fuel. The data in the US Energy Information Administration (EIA) Annual Electric Generator Report for 2009 gives the breakdown in Table 20.

Table 20 US waste coal firing units

Waste coal	Primary fuel		Supplementary fuel		Total units	Total rating, MW
	No of units	Rating, MW	No of units	Rating, MW		
FBC	22	2017	4	917	26	2935
Other			4	23	4	23
PC	2	117	26	9395	28	9512
Totals	24	2134	34	10335	58	12469

West Virginia

In West Virginia there are at least 864 coal production residue disposal sites including reclaimed and

Table 21 Inventory of West Virginia slurry injection

Year	Known slurry, thousand m^3/y	Known projects	Projects with known volumes	Projects with unknown volumes	Projects with possible injection
1958	0.4	1	1	0	0
1959	0.4	1	1	0	0
1960	0.4	1	1	0	0
1961	0.4	1	1	0	0
1962	0.4	1	1	0	0
1963	>0.4	2	1	1	0
1964	>0.4	2	1	1	0
1965	>0.4	2	1	1	0
1966	>0.4	2	1	1	0
1967	>0	1	0	1	0
1968	>0	1	0	1	0
1969	>0	1	0	1	0
1970	>0	3	0	3	0
1971	>0	3	0	3	1
1972	>0	4	0	4	1
1973	>0	7	0	7	1
1974	>92	7	1	6	1
1975	>92	9	1	8	1
1976	>92	9	1	8	0
1977	>92	9	1	8	0
1978	>368.7	10	2	8	0
1979	>404.5	12	4	8	0
1980	>840.5	18	10	8	0
1981	>601.1	20	11	9	0
1982	>399.8	21	12	9	0
1983	>784.6	19	9	10	0
1984	>1345.6	23	12	11	0
1985	>1756.3	19	11	8	0
1986	>1723.8	17	10	7	0

un-reclaimed impoundments and dry piles. Of these, 112 active and 94 abandoned impoundments were identified in the AML inventory. It is estimated that overall these deposits represent more than 785 Mt of resource in the state, after allowing for utilisation rates of up to 2.2 Mt/y (Kent and Risch, 2006).

Inventorying of West Virginia slurry injection (Smith and Rauch, 1987) demonstrates clearly the impact of the 1977 SMCR Act on the extent of this practice which increased dramatically in the ensuing years (*see* Table 21).

Kent and Risch (2006) identify several CFBC facilities constructed or planned in WV for utilisation of coal production residues:

- Morgantown Energy Facility – ~250,000 t/y, also uses unwashed low heating value, non-utility grade coal.
- Grant Town Power Plant – 80 MW plant utilising ~600,000 t/y of which ~35% is from slurry impoundments, both wet and dry. The plant fuel blend typically is 60% coarse/40% fines drawn from several local sites some of which have now been exhausted and fully reclaimed (American Bituminous Power Partners, 2006).
- North Branch – ~300,000 t/y, much from an unreclaimed AML site at Bayard, West Virginia. However, the plant has now been mothballed.
- Western Greenbrier – ~1,000,000 t/y from an acid mine drainage site at Anjean, West Virginia. Availability of ~20 Mt at four other sites was also confirmed with further piles to be prospected. However, the project was abandoned in September 2008.

Illinois

Illinois mining annual statistics report throughput and reject rates for individual coal preparation plants from 2000 to 2009. The information from these reports is summarised in Table 22 and Table 23.

Table 22 Illinois annual coal and reject production statistics (IDNR, nd)

Year	Total processed, t/y	Rejected, %	Total rejected, t/y
2000	42,892,806	34.3	14,717,830
2001	41,806,766	37.9	15,827,211
2002	45,372,233	42.1	19,107,103
2003	43,521,659	36.3	15,783,452
2004	45,507,720	37.7	17,177,775
2005	44,775,203	44.1	19,736,023
2006	41,290,216	42.3	17,476,904
2007	41,378,553	43.8	18,131,170
2008	47,561,404	42.3	20,138,891
2009	53,072,988	39.0	20,702,022
Overall totals	447,179,548	40.0	178,798,382

Table 23 Performance of coal preparation plant technologies in Illinois (IDNR, nd)

Technology	Reported reject rate, %
Rotary breaker	1–15
Heavy media	8–60
Water jig	25–56
Jig and heavy media	35
Jig and spiral	15–28

Rajchel (1995) reports an estimate of about 4 Mt/y fine material deposited in impounds whilst Rapp and others (1995) estimated that about 2 Mt/y of recoverable coal fines were discarded in this way. This was based on an estimated reject rate of 5%. Extensive deposits of coal material were built up in the 1920s to 1940s when material below about 50 mm was considered to be fines and as such was dumped.

Khan and others (1986) reviewed coal production residues in two mining districts in Illinois. Analysis of two slurry deposits showed the highest potential for recovery. However, these opportunities were lost as they were buried during subsequent land reclamation work.

Kentucky

Honacker (2005) estimated that about 500 Mt of fine coal was stored in impoundments in Kentucky with around 3 Mt/y being added to this total.

Indiana

An extensive review of Indiana's coal slurry deposits (CSD) was based on pre-existing data which were used to estimate the thickness of each CSD from which their volumes were calculated. The estimated total volume of CSD in Indiana was in the range 94–136 million cubic yards (~72–104 million m^3) representing 22–69 Mt of recoverable coal. Coal slurry, at active coal-preparation facilities, in some water-filled impoundments near to inactive operations, in excavated pits of unknown depth, and in graded spoil deposits, was not included in the estimate. The Center for Coal Technology Research (2009) reported an extensive programme of sampling and analysis that was undertaken at ten mine sites and the properties of the material are summarised in Table 24.

Pennsylvania

Recovered coal production residues have been used for decades for power generation in Pennsylvania. Pennsylvania Power & Light started using fine coal production residues (anthracite silt) in the 1940s and had two power plants (at Shamokin Dam and Holtwood) where coal fines were used without further processing. The Sunbury power plant at Shamokin Dam is now owned by Corona Power. It has four PC fired units commissioned over a five-year period (75 MW in 1949, 90 MW in 1949, 104 MW in 1951 and 156 MW in 1953). The Holtwood PA plant (Harrison and Akers, 1997) took fines dredged from the impoundment (Lake Aldred – used for the Holtwood hydro plant) and waste coal dredged from Safe Harbor Dam impoundment upstream but it was demolished in 1999. Table 25 lists the sixteen FBC plants in Pennsylvania that burn coal production residues.

From 1988 to the end of 2003, coal refuse plants in Pennsylvania used 88.5 Mt of coal refuse, mostly from 'legacy' refuse piles. On average they burn about 7.5 Mt/y of coal refuse as fuel, mostly from 'legacy' coal refuse piles (PADEP, 2004).

6.2 Europe and Eurasia

The coal mining and preparation histories of European countries are diverse. In several countries mining continued for many decades but during the second half of the 20th century production has reduced dramatically (UK) or ceased altogether (France, Belgium, Netherlands). However, Germany and some of the Eastern European countries continue to produce and prepare large amounts of coal.

6.2.1 Albania

In the late 1980s coal production rose to 2.2 Mt/y but between then and 2000 production collapsed to 0.3 Mt/y by which time 3 million m^3 of coal mining waste had been accumulated according to the United Nations Economic Commission for Europe (2002).

6.2.2 Belgium

Coal production in Belgium extended back into the 19th century. In 1890, coal production totalled some 20 Mt. Around the turn of the century there were 265 active collieries all in the Walloon area of Southern Belgium and their output amounted to about 20 Mt/y. In 1917, coal mining started around

Table 24 Examples of properties of Indiana coal slurry deposits (Center for Coal Technology Research, 2009)

Mine	No of bore holes	No of samples	Moisture, % ad	Moisture, % ar	Ash, % ar	Sulphur, % ar	CV, kJ/kg ar	CV, kJ/kg maf
Airline	11	99	2.1		42.4	4.4	16.6	29.4
Buckskin	7	17	4.3		29.0	2.7	20.0	29.9
Chinook	14	81		28.3	30.5	3.2	13.0	31.0
Friar Tuck	9	37	3.1	28.4	28.1	2.1	18.8	31.8
Green Valley	9	23	4.4		20.9	5.1	22.7	30.9
Hawthorn	11	55	1.5		45.2	5.8	15.4	27.7
Lynnville	6	36	4.0		35.0	4.3	19.0	31.0
Minnehaha	18	74		31.5	20.2	2.2	16.0	31.8
Otter Creek	4	4	5.0		26.7	2.6	20.7	30.3
Tecumseh	4	28	4.7		35.9	8.9	16.7	27.8

Table 25 Pennsylvanian power plants fired on coal production residues.

	MW	In operation	Coal type
Colver Power Project	102	1995	bituminous
Northampton Generating Station	134	1995	anthracite
Scrubgrass Generating Plant	83	1993	bituminous
Panther Creek Energy Facility	95	1992	anthracite
John B Rich Power Station	79.4	1988	anthracite
WPS Westwood Generation	30	1988	anthracite
Chester Operations	59	1987	anthracite
Piney Creek LP	32	1992	bituminous
Mount Carmel Cogen	46.5	1990	anthracite
Cambria County Cogen	98	1991	bituminous
Ebensburg Power Co	48.5	1991	bituminous
Seward Generating Station	521	2004	bituminous
St Nicholas Cogeneration Plant	80	1990	anthracite
NEPCO	59	1989	anthracite
Wheelabrator Frackville Energy Co.	48	1989	anthracite
Archbald Power Station	25	1990-97*	anthracite

* converted to operate on landfill gas.

Limburg in the north-east of the country. Toward 1950 the number of pits had declined to 150 but in 1952-53, national coal production reached a record peak of 30 Mt, maintaining this level until the late 1950s. Thereafter output gradually declined so that by 1981 only one pit remained in the South and five in the North of the country, and the last colliery ceased production in 1992 (Euracoal, 2008; van der Haagen, 1982). The recovery of coal from production residues was significant in comparison to the total production from 1978 to 1981 (*see* Table 26).

Table 26 Belgian coal production, 1950 to 1981, Mt/y (van der Haagen, 1982)

	Output	Estimated secondary coal recovered
1950	18.3	
1952	30.0	
1960	14.7	
1970	7.6	
1973	6.0	
1974	5.8	
1975	5.3	
1976	5.2	
1977	5.1	
1978*	6.6	1.9
1979	6.1	1.6
1980	6.3	2.0
1981	6.1	2.0

* from 1978 includes secondary coal recovered from tip reworking

6.2.3 Bulgaria

From 1981 to 2008 average coal production was about 30 Mt/y (BP, 2010). Table 27 shows the breakdown by type of annual coal production in 1990 (Davcheva-Ilcheva, 1994).

Table 27 Breakdown of Bulgarian coal production in 1990 (Davcheva-Ilcheva, 1994)

Type	Production Mt/y
Lignite	27
Brown coal	4.5
Black coal	0.24
Anthracite	0.05

Of this only about 13% (4 Mt of production was prepared using gravity and flotation technologies. This resulted in over 1 Mt of solid waste. As the rate of coal production has been fairly steady over the past 30 years stock of more than 30 Mt is feasible.

At the Bobov Dol mine the brown coal produced is considered brittle with around 10% of the material extracted being fine. About 0.8 Mt of coal preparation fines were accumulated in the tailings pond between 1967 and 1987. Analysis of the deposited fines indicated that between 45% and 70% of the material accumulated is of a quality that could meet the fuel specification of the 630 MW (3 x 210 MW units) Bobov Dol power station. The investigations found that this material could be recovered using spiral concentrators (Kuzev, 1998). Since privatisation of the station in 2008 the units have been undergoing upgrades, which are expected to be complete in 2015, but no indication was found that recovered fines have featured in the fuel supply to the plant.

6.2.4 Czech Republic

By 1876 hard coal production in the Czech Republic had reached 4.55 Mt/y, of which 1.50 Mt/y was from the Ostrava-Karvina coalfield and the other two-thirds from other coalfields. The development of the Czech coal mining industry since then is summarised in Table 28.

The Ostrava-Karvina coalfield is the only source of hard coal and each year about 18 Mt of coal mine wastes and tailings are produced there, together with large amounts of wastewater and slurries. About 1 Mt/y is used to backfill underground mines, 8–10 Mt/y for land reclamation and 2–4 Mt/y for civil engineering projects. Smaller amounts supply raw material for brick and cement plants. Some is also used as a component of the fuel in a fluidised bed combustion unit. 0.5 Mt/y of wastes and low-quality fuel are processed using the Haldex process to recover saleable coal (Hlavata-Sikorova and Vitek, 1990).

Table 28 Saleable coal production in the Czech Republic 1876 to 2004, kt (Fecko and others, 2006)

	Hard coal			Brown coal			Total in Czech Republic
	Ostravsko-Karvinsky coalfield	Other coalfields	Total	North-Bohemian brown coalfield	Sokolov brown coalfield	Total	
1876	1,500	3,050	4,550	4,250	530	4,780	9,330
1900	5,770	4,030	9,800	14,670	2,690	17,360	27,160
1930	10,670	3,690	14,360	14,780	3,610	18,390	32,750
1950	13,720	3,780	17,500	19,830	6,260	26,090	43,590
1960	20,868	5,530	26,398	39,080	14,600	53,680	80,078
1970	23,856	4,339	28,195	54,520	19,890	74,410	102,605
1980	24,689	3,512	28,201	66,700	20,450	87,150	115,351
1990	20,840	2,350	23,190	60,700	11,850	72,550	95,740
2000	13,855	1,000	14,855	39,510	6,692	46,202	61,057
2004	13,272	30	13,302	37,984	6,064	44,048	57,350

6.2.5 France

For many years, prior to the final closure of the French coal industry, efforts were made to utilise the coal production residues with combustion of anthracite culm/GOB from about 1950 (Leonard and Lawrence, 1973). This approach continues, with coal being recovered from the slag heaps in the Nord Pas De Calais region. There were at one time more than 600 of these, but by 2008 this had been reduced to 300 (Masalehdani and others, 2008). The recovered material is prepared using mobile washeries to produce 'relavures' which is burnt in the down-fired (wall-fired) Hornaing 3 plant. This plant has been operating since 1970 and will close in 2015. However, the composition of these heaps is mainly carbonaceous shale and so they are comprised of mainly mining rather than preparation residues.

Some French plants were designed specifically to operate on mine waste with this being the only type of fuel permitted in some plants such as Unit 4 at the Emile Huchet plant. From 1958 to 1990 this was a 125 MW CFBC but it was then repowered as a PC fired unit. Up to 2004 the fuel was a CWM (67% solids essentially 'schlamms' from coal preparation plants). Approximately 2.6 Mt/y of material was processed to prepare the CWM for the CFBC.

Table 29 Hard coal tailings production, Mt/y (Popov, 2007)

Year	Tailings
2000	30.8
2001	26.9
2002	26.5
2003	26.7
2004	28.9

6.2.6 Germany

Hard coal production declined from around 50 Mt/y in 1995 to around 25 Mt/y in 2005. Around half the material mined is 'useful raw material'. According to Deutches Steinkhol (DSK) coal production wastes are either injected into underground workings, or landscaped. Tailings are not regarded as waste by DSK (Popov, 2007). The tailings rates for the years 2000 to 2004 are shown in Table 29.

6.2.7 Kazakhstan

United Nations Economic Commission for Europe (2000) found that 3.5 billion m^3 of coal tailings have accumulated in Kazakhstan, occupying an area of 10,000 ha. As in some other Eastern European and Eurasian countries the coals have significant radioactive contents. The relatively high ash levels in tailings leads to relatively higher levels of activity than for the whole coal.

6.2.8 The Netherlands

Coal was mined in the Netherlands from the early 1900s, and until the mid-1970s hard coal was deep mined in the Limburg area in the south of the country. From 1915 to 1968 lignite was extracted from surface mines in the north near to Eygelshoen and Hoensbroek (Euracoal, 2008). In 1938 production equalled 13.5 Mt/y but as a result of the Second World War output dropped to 5 Mt/y by 1945 although this quickly recovered and by 1948 it had reached 11 Mt/y. Typically 30–35% of ROM was reject. However, high mining costs drove research into coal preparation and techniques for recovery of relatively high ash middlings, leaving rejects typically with >75% ash (Griffen, 1951). This suggests that there may not be substantial deposits of recoverable fine organic coal.

6.2.9 Poland

Coal production has slowly declined from a peak of over 266 Mt/y in 1985 and 1986 to 144 Mt/y in 2008 (BP, 2010). In 2004 there were 50 coal preparation plants, 40 at coal mines and 10 at separate locations and a breakdown of their capabilities is shown in Table 30.

In Poland 15 Mt/y of hard coal mining residues are produced of which around two thirds are utilised (Magiera, 2007). Large amounts of washery residues are also deposited. Coarser residues are utilised in various ways but no uses for fines were identified (*see* Table 31).

Table 30 Polish coal preparation plants (Blaschke and others, 2006)

No of plants	Fraction treated	Size fraction, mm	Capacity, Mt/y of raw coal	Utilisation, %
50	Coarse/medium	>20/>10	90.8.	44
38	Fine	20/10–1.0/0.5		79
16	Slimes	1.0/0.5–0	10.1	68

Table 31 Utilisation of Polish coal production residues (Góralczyk, 2009)

Waste type	Percentage used	Usage
Waste coal	27	Hydro-dam embankments in rivers Road and railway embankments Marine embankments and coastal protection
	9	Coal recovery by reprocessing
Colliery spoils	0.5	Light aggregate concrete Bricks and tiles
Flotation tailings	–	No industrial applications

About 5.5 Mt/y of coal slimes are produced and the estimated stock in the late 1990s was 16 Mt, having ash contents between 40% and 65% (EUREKA, 2004).

The complexity of some residue deposits is illustrated by the Bukow coal mining waste dump. Between 1976 and 2001 coarse and fine coal preparation wastes were deposited together. The coarser wastes comprising 59% were from dense medium separators and the finer comprising about 41% from jigs. From 1995 flotation slurry with –1 mm material comprised about 4.7% of the discarded material, along with about 1.8% fly ash and slag from the mines power plant (Stefaniak and Twardowska, 2009).

Polho Sp z o o (www.polho.slask.com.pl) operates a fines rewashing plant at the Dębieńsko mine tailings ponds in Czerwionka – Leszczyny. Fines are dug from the ponds and transported by truck and conveyor to the plant. Here they are re-dispersed in water and organic coal is separated from clays in flotation cells. The product is dewatered using vacuum drum and belt filters. Thermal drying is used to produce the desired product quality. Since it commenced operation in October 1992 about 5 Mt have been processed. An industrial trial of the plant gave a concentrate yield of about 41% and the properties of the feed and concentrate materials are shown in Table 32.

Table 32 Results of POLHO plant industrial trial (Blaschke and Blaschke, 2005)

	Feed	Concentrate
CV, kJ/kg	11,587–12,946	22,160–22,585
Ash, %	27.0–29.9	7.5–9.3

Haldex SA (www.haldex.com.pl) based in Katowice was established in 1959 as a joint Polish/Hungarian operation designed to alleviate the fuel shortage in Hungary by use of coal recovered from Polish coal production residues. It has recovered over 17 Mt of coal fines over the past 50 years. It now has four plants for coal and aggregate recovery, two for aggregate recovery (from mining spoil) and three for granulation of washery slimes (total granulation capacity 210 t/h).

In 2009 the 460 MWe Łagisza supercritical CFBC power plant entered service and has operated successfully since then (Hotta and others, 2010). Although its main design fuel is bituminous coal it is capable of burning a wide variety of fuels including fine coal residues.

6.2.10 Romania

The output of the Romanian coal industry declined from 53.2 Mt/y lignite and 8.3 Mt/y of hard coal in 1989 to 20.1 Mt/y lignite and 2.8 Mt/y of hard coal in 1999. Since then, up to 2005, lignite production recovered to around 30 Mt/y and hard coal production stabilised at around 3 Mt/y (Florea, 2008). In 1998 about 35.7 Mt of residues were generated from production of 22.9 Mt coal (United Nations Economic Commission for Europe, 2001). A report from the PECOMINES project covering mining issues in the then pre-accession states of the EU, identified a total amount of mining waste from the Motru lignite mines in the Oltenia coal basins as approximately 224 million m^3, covering 944 ha (Jordan and D'Alessandro, 2004). However this is likely to be mainly overburden from the opencast mining operations which started in 1967.

6.2.11 Russia

According to the history of Russian mining from russiancoal.com (www.russiancoal.com/coalminingrussia/briefrussia.html) coal mining in Russia commenced in 1691. By 1860 production had reached 121 kt/y, rising to 12 Mt/y in 1900 and 34.5 Mt/y in 1916. From 1917 to 1919 production fell dramatically as most mines were closed. From 1920 to 1928 many mines were re-opened and the first coal preparation plants were built. From 1928 to 1937 about 100 Mt of mining capacity were added and mechanisation commenced and in 1934-35 opencast mining commenced. Through the

1960s and 1970s mechanisation increased and production grew to its peak of 425.4 Mt in 1984. Production declined from this point but started to grow again in 1999 and reached 326.5 Mt in 2008.

From 1999 to 2006 around 30% to 35% of Russian coal production was processed through preparation plants. Assuming that this was the case over the period from 1984 to 2008 and that 15–25% of material was rejected, total amounts of residues from that period are in the range 360–600 Mt.

SUEK operates 33 coal mining enterprises and eight preparation plants or modules. They reported that their production of waste from coal preparation rose from 0.13 kg/t in 2007 to 16.1 kg/t in 2008 (SUEK, 2008).

In the Kuzbass 30 Mt of sludge with 34–56% of ash, 50% moisture are stored in lagoons (Baychenko and Evmenova, 2008) whilst there are 5 Mt coal slurries in impoundments in the Pechora region with 0.15 Mt of slurry added to this each year.

Production of coal water mixtures from washery residues is an option commonly proposed in Russia for replacement of oil and gas in power plants and industrial furnaces. The benefits identified include:
- lower NOx production due to lower flame temperatures;
- more efficient SO_2 capture;
- more effective ash capture due to formation of highly porous particles;
- no risk of fire or explosion during transport and storage.

Khodakov (2007) reviewed progress on development of such CWM in Russia. Investigations into their production and use started over 60 years ago. From the start this was viewed as a means of disposing of coal slurries from washeries thus avoiding the costs associated with dewatering them prior to use. However, the heterogeneous nature of these materials was found to be problematic and none of the approaches tried proved to be economically feasible. Therefore projects for burning these slurries without further preparation have not been implemented.

In 2008 Foster Wheeler were contracted to supply a supercritical 330 MWe CFBC to JSC Energo Mashinostroitelny Alliance with commercial operation scheduled for the end of 2012. The design fuel for this plant is a combination of anthracite and bituminous coals and anthracite slurry (Hotta and others, 2010).

6.2.12 Spain

There is no register of amounts of coal wastes in Spain. However, there is concern over the safety and environmental implications of the stocks of these materials. Work has focused on remediating sites and re-vegetation rather than on coal recovery (Rubiera, 2011).

HUNOSA's, La Pereda Thermal Power Plant, is a 50 MWe atmospheric CFBC plant that operates for 6500 h/y fuelled by a mixture of 400,000 t/y of waste fines, a small percentage of ROM coal and wood waste (Hunosa, nd).

6.2.13 Turkey

Most of the Turkish lignite, apart from the production from some small mines, is washed prior to use. The level of fines in lignite production is at least 10% although in some cases it is significantly higher such as at the Corum Alpagut mine where it is reported as being 20% of the washed coal (Altun and Hiçyilmaz, 2001). Although there is a desire to reduce the amount of fines discarded there are no industrial efforts to recover this material (Hicyilmaz, 2011).

6.2.14 Ukraine

Small-scale coal mining had started in the Ukraine by 1820 and by 1869 output had reached 7 kt/y. Around 1869 several new mines opened around what is now Donetsk, to feed a new metallurgical plant. By 1913 the Donbass (Donetsk Basin) was producing 87% of 'Russian' coal. There have been over 400 coal mines in the region with 40 located within the Donetsk city limits. At the end of 1999 there were 241 underground mines and three surface mines. By 2004 this was reduced to 192 and subsequently to 162 underground and three surface mines (Byrnes, nd). Most of these mines are in Donbass which is the main coal producing region of Ukraine, contributing up to 80% its output.

Accumulation and storage of solid coal waste around the Donetsk region is recognised as an important issue. In 2002 it was estimated that in total there were nearly 1.3 Gt of coal production residues with annual generation of 60 Mt with no more than 17% of this being utilised (Ogarenko, 2010). These residues fall into two categories:

- dry waste of coal mining and preparation – 7190 ha under about 300 heaps of tailings
- wet coal wastes – 4010 ha.

Table 33 shows examples of the characteristics of wet and dry fine coal preparation residues.

Table 33 Examples of the characteristics of dry and wet fine residues (Bondarenko and Pilov, 2008)

Sizes in mm	Slime		Dry fines	
	Clay, %	Coal, %	Clay, %	Coal, %
<10 >2.5	–	–	4.59	11.62
<2.5 >1.0	–	–	6.52	16.52
<1.0 >0.315	–	–	7.71	19.52
<0.315 >0.05	14.13	28.43	7.86	19.91
<0.05	19.07	38.37	1.63	4.13
Total	100		100	
Free moisture, %	17.2		8.0	

Dry residues

The dry materials have 10–30% organic coal content, and have the potential to be reprocessed to produce a fuel with 30–40% ash, suitable for CFBC fuel. The distribution of these materials in the vicinity of the Lugnask CFBC plant is shown in Table 34.

Table 34 Coal production residues in Lugansk region (Kortechvoi and others, 1998)

Region	Amount accumulated, Mt	CFBC fuel potential, Mt
Shakhtersk-Torez	90	18–20
Krasny Luch-Anthracite	75	14
Rovensky	25	4.4
Sverdlovsk	35	8

Wet residues

Various estimates have been presented of the amount of wet coal preparation residues in the Ukraine. Stone & Webster Management Consultants (1998) concluded that the total amount of fine residues from coal washing stocked at the time ran to ‘several hundred Mt’ (700 Mt of tailings) and that of this around 180 Mt were economically recoverable as fuel for FBC boilers. The rate of accumulation was considered to be around 10 Mt/y.

Negreev and Papushin, (1999) reported that the Donbass region had 150 Mt of flotation residues with 55% to 70% ash and about 10 Mt/y are added to this.

Shevkoplyas and Litvinenko (2000) noted that there were 56 settling ponds, containing 160 Mt of coal slurries or flotation residues. The ash content ranges from 30% to 70% and organic coal comprises 30–50%.

Kortechvoi and others (1998) divided the wet residues into three categories according to ash content:

- <40% (limited amount);
- >55% (not suitable for combustion without further processing);
- 40% to 55% (considered suitable as CFBC fuel without further washing).

They estimated that the latter category represented 50–60 Mt accumulated in the Lugansk and Dontesk regions with about 10 Mt being anthracite. Shipachev and Fedorov (1998) estimated that there were 120 Mt of silts stored in Ukraine of which 40 Mt had characteristics which would allow it to be economically re-mined and prepared.

Efforts have been made to recover these residues. In about 2000 Ecotech opened a plant to process coal slurries using spiral concentrators. It had a potential output of 1200 to 1300 t/d of concentrate. The concentrate was suitable for metallurgical production, power plant fuel and for the manufacture of electrodes. However, various obstacles to the operation of the plant have been encountered due to local political and business issues (ZN,UA, 2001), stretching over the following ten years (Investgazeta, 2002; IU.ORG.UA, 2011).

The Sadovaya Group operates in Ukraine’s Donetsk and Lugansk Regions. Along with its anthracite mining operations it controls 16 coal waste dumps and tailings ponds and the estimated reserves range from 1.3 to 1.4 Mt and from 5.5 to 6.5 Mt respectively. It has facilities with capacity for recovery of 60 kt/y of coal from these stocks. However, output has dropped in recent years (2007, 58.2 kt; 2008 6.1 kt; 2009, 5.4 kt) but recovered to 12.6 kt in the first half of 2010. They state the intention to launch a full-scale waste recovery business in 2011, building two new facilities (one each for the waste dumps and for the tailings ponds), which will produce 738 kt of recovered coal in 2012. The facilities will use dense medium cyclones. The costs of recovery are estimated to be 25–30% of those for freshly mined coal (Sadovaya Group SA, 2010).

Bondarenko and Pilov (2008) investigated the options for pelletising coal concentrates from coal preparation residues (amongst various other potential fuels) using a range of binders. They found that the greatest strengths were produced by inclusion of 8% gluten or 10% dump oil.

6.2.15 UK

The UK has a long history of coal mining which started as numerous private enterprises. Passing through a period of public ownership mining is now carried out by a limited number of private companies but various responsibilities were retained under public responsibility mainly administered by the Coal Authority. However, the Coal Authority only owns about 40 waste heaps, which represents a small proportion of the certainly hundreds and perhaps thousands of mining sites abandoned in the UK. In some cases settlement lagoons are associated with the heaps but these are for collection of run-off rather than impoundments for coal preparation slurry. Within heaps composition may vary with bands of high concentrations of organic coal. Slurry settlement ponds are sometimes found buried within spoil heaps.

A Department of the Environment report (2009) contains a file note stating that the National Coal Board (NCB) had carried out surveys of tips having ‘a significant coal content’ and categorised them as:

- tips formed solely from run-of-mine material at collieries where there has never been a washery;
- tips where an antiquated washing system was or, in isolated cases, still is, in use.

It also notes that, as of March 1980, 11 contracts were in operation for rewashing such tips at the rate of about 0.6 Mt/y though this material still had significant ash content.

In 1981 it was estimated that there were 345 active tips, 246 closed tips that were associated with active tips, and 493 disused tips associated with closed mines (Department of the Environment, 2009). Many abandoned colliery sites became the responsibility of local authorities and the negotiations between the relevant government departments (Department of Environment and the Inland Revenue), local authorities, the National Coal Board (NCB) and companies contracted to recover coal material were sometimes protracted. Discussions centred around the value of the heaps as an inorganic mineral source, as well as the value of the coal material that they might be found to contain. Issues arose over whether the NCB would sub-contract rewashing of tip material. At times of overproduction from working collieries any additional coal from recovery projects was not viewed favourably.

In the UK older tips dating from before the Second World War have a much higher organic coal content than more recent ones. In particular those dating from the late 1800s have the highest levels, up to around 30%. Department of the Environment (2009) contains a file note which comments: ‘There were high losses from coal preparation plants in the old days (pre-1900), if you counted fine coal – this was however, a relatively small proportion of output and much was packed underground.’

Formal recording of these sites was not required and no formal inventory is available. Over time, knowledge of locations of coal production residues has been lost.

In October 1966, 144 people were killed when a tip of coal waste slid onto the village of Aberfan in Wales. In the wake of the disaster many heaps in the UK were reduced in size. The material from Aberfan was moved further up the same valley and restacked. Many other sites have been re-profiled and returned to use, mainly forestry and agriculture, but in some cases they have even been built over. Such locations are in any case unlikely to be revisited for coal recovery unless they are found to present a safety or environmental hazard. However, many of the higher quality residues have already been recovered and the material rewashed and used.

The Building Research Establishment estimated in 1974 that there were 3 Gt of spoil heaps in the UK, with spoil being produced at a rate of 50 Mt/y with demand for the rock at only 7–8 Mt/y.

Monitoring and recording is required for tips created since the 1969 Mines and Quarries Tips Act . Thus for these more recent tips the Coal Authority holds records of the annual measurements of the tip profiles. This information would enable tip volumes to be estimated provided that the tip is in the same condition as when it was abandoned. This is accessible via the Authority’s Mines Records department (Wilson, 2011).

Since at least the middle of the 20th century efforts have been made in the UK to remove stocks of coal production residues or to avoid stocking new material. Two power stations were built for this purpose at Methil (commissioned in 1965, mothballed from 2000, demolition commenced in 2010) and Barony (operated 1956 to 1983, cooling towers and chimney were demolished 1986). These two stations each consisted of 2 x 30 MW GEC turbines feed by four Babcock & Wilcox coal slurry fired boilers. They were specifically designed to burn slurry from the washeries of the Fife coalfield. Later as the mines closed the heaps of coal production residues, known locally as ‘bings’ were used to continue operation. Once all fuel was consumed the plants were closed.

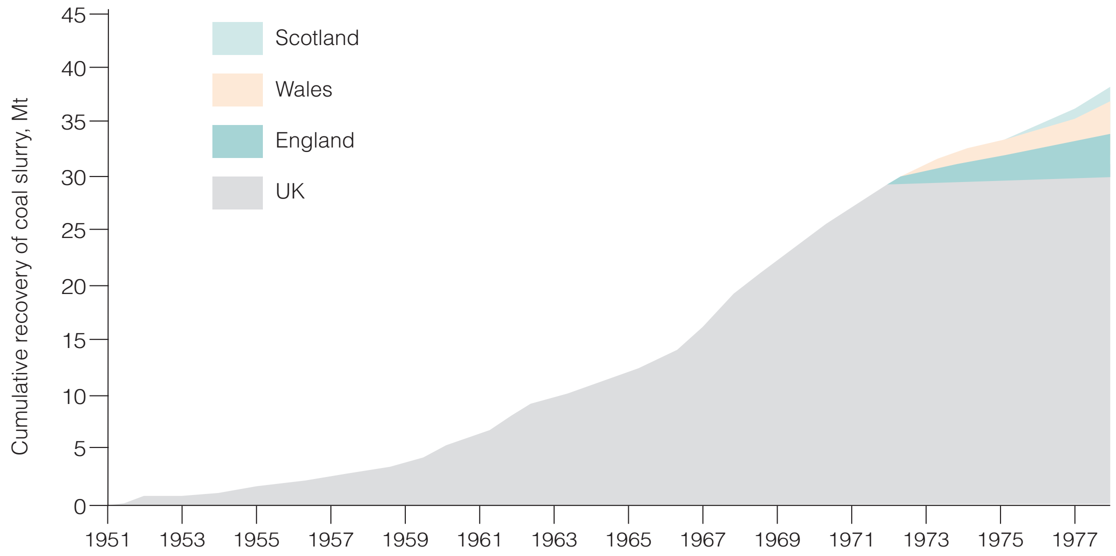

Figure 16 Coal slurry recovered in the UK (Department of the Environment, 2009)

By 1972 a rolling programme of land reclamation was operating in the Durham coalfield: the NCB wanted this approach to be adopted generally and it was agreed in Lancashire and some other areas. According to Department of the Environment (2009), the United Kingdom Mineral Statistics for 1979 showed figures for recovery of coal as slurry from dumps, ponds, mines, etc, which over the period 1951 to 1978 totalled about 38.5 Mt (Figure 16).

Battersby and others (2003) stated that there were around 20 Mt of 'ultrafine coal' residues accessible in the UK which they based on communications with a major UK coal company.

The UK Department for Energy and Climate Change (DECC) statistics now include an estimate of coal slurry use. These statistics are based on the output returns from all producers (DECC, 2009). However, the 'slurry use' estimate (2.8% of production in 2009) includes all output that is not included in deep mine and opencast output returns and not solely recovery of old slurry impoundments. It also includes 'tip coal' (recovered by rewashing of spoil heaps) and 'incidental coal' (extracted during essential development activities at mining sites, such as roadway construction). Coal slurry impoundments at operating mines are cleared once they have been filled. All recent mine closures have been accompanied by a formal closure process and this includes site clear-up, but this is controlled by local planning regulations which are more focused on land reclamation than fuel recovery opportunities (Brewer, 2011).

A long-standing approach to dealing with impounded fines is for them to be dried (or allowed to dry) prior to sale directly to power plants as fuel. Department of the Environment (2009) refers to this as the approach in the early 1980s. Since 2009, Drax – the UK's largest coal-fired power plant – has been taking recovered pond fines, starting at around 1% of fuel in the first half of 2009 (Drax Group plc, 2010) and rising to 3% in 2010 (Drax Group plc, 2011). In 2009 116 kt were delivered and about 400 kt in 2010. This level is expected to rise further. The station could fire this material at levels up to 15% of coal feed, but there are handling issues in wet weather which limit the rate of usage. The material is simply dug out of old impoundments and delivered to the station where it joins the main coal feed after passing through a shredder. No other special arrangements were required to enable the station to fire this material (Ghent, 2011). Drax supplier, Hargreaves Services, reported growth in harvesting of coal fines from their Maltby fines impoundments and development of markets both for the fines alone and in blends. (Hargreaves Services plc, 2010). At UK Coal's Kellingley colliery dried coal slurry from old settling ponds is being shredded and blended directly into power plant fuel (CDP Plant, 2010).

6.3 Africa

The only coal producer of significance in Africa is South Africa, representing more than 90% of the total. Production in Zimbabwe has declined steadily since the early 1990s whilst South Africa's has nearly doubled since the beginning of the 1980s.

6.3.1 South Africa

Coal sales figures dating from 1885 to 2008 show a cumulative total of about 7 Gt, with the bulk of this in the past 30 years (Figure 17).

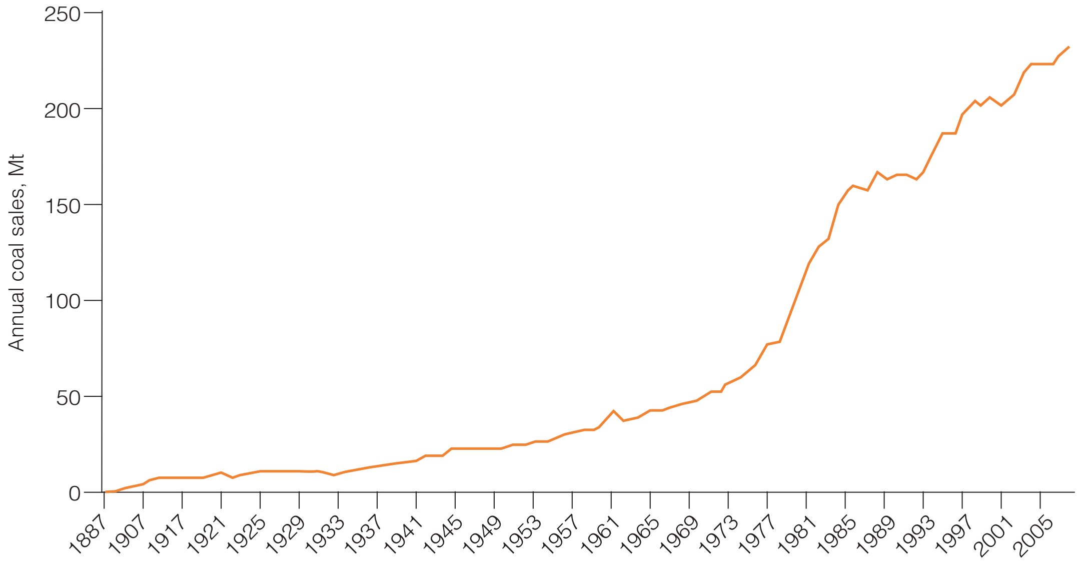

Figure 17 South African coal sale history (Ikaneng, 2010)

When de Koort (2000) inventoried South African coal preparation plants 58 were identified although five of these were closed. A range of configurations were found with various combinations of equipment used (*see* Table 35). The most common configuration was WEMCO + dense medium cyclones + spiral concentrators. Only seven of the plants incorporated flotation technology for fine coal cleaning. South African coals tend to be high in near gravity material and in general have poor flotation characteristics (Peatfield, 2003). Thus they are difficult to wash and this presents a particular challenge when utilisation of discarded material is considered. The 2010 directory of South African mines shows around 49 preparation plants including washing, with several others that only included crushing and screening stages (Ikaneng, 2010).

Historically coal preparation residues were dumped with little concern for environmental impacts and lost value but has now been recognised as a particular problem in South Africa for over 20 years. More recently, as reserves diminish and demands increase, there has been increased attention on the potential of these materials. The coal production residues dumped in South Africa have twice been inventoried, most recently in 2001 and previously in 1986. The materials inventoried included fine and coarse discard, slurry and unsold duff coal (washed –6.3 mm fraction). The total from the 2001 inventory was 1,120.853 Mt (Wagner, 2007).

Of the 262 Mt of ROM in 1996, 55 Mt (about 21%) were discarded (Wagner, 2007) though more recent estimates are that the fines discard is about 45 Mt/y of which about a quarter is in slurry (Swanepoel, 2008). Assuming that discard rates have continued at a similar level relative to production the accumulated material will have reached about 1.7 Gt although the Department of Minerals and Energy (DME) state a figure of 2 Gt discarded since 1992.

Table 35 South African coal preparation plant inventory (de Koort, 2000)

Colliery	Plant capacity,, t/h	Status	Barrel washers	Drewboy vessel	Tesca vessel	Wemco drum	Larcode ms	Norwalt	Jig	DM cyclones	Spirals	Flotation
Arnot	450	Operating		Y								
Arthur Taylor Plant 1	550	Operating				Y				Y	Y	
Arthur Taylor Plant 2	280	Operating		Y						Y	Y	
ATCOM	1000	Operating				Y				Y	Y	
Bank 2	950	Operating				Y				Y	Y	
Bank 5	150	Operating						Y		Y	Y	
Boschmans (Tweefontein)	550	Operating				Y				Y	Y	
Delmas	500	Operating				Y				Y	Y	
Dorstfontein	230	Operating				Y				Y	Y	
Duvha	700	Operating					Y					
Eikeboom	200	Operating						Y		Y	Y	
Elandsfontein	250	Operating				Y				Y	Y	
Forzando	325	Operating								Y	Y	
Goedehoop	1100	Operating				Y				Y	Y	
Graspan	140	Operating				Y				Y		
Greenside	400	Operating								Y	Y	
Kleinkopje	1500	Operating				Y				Y	Y	Y
Klipfontein	750	Closed						Y		Y	Y	
Koornfontein	1300	Operating				Y				Y	Y	Y
Lakeside East	220	Operating				Y				Y	Y	
Landau (Kromdraai)	1100	Operating		Y						Y	Y	
Leeuwfontein	180	Operating								Y	Y	
Leeuwpan	550	Operating				Y				Y	Y	
Middelburg	1050	Operating				Y				Y	Y	
New Clydesdale	300	Operating								Y	Y	
Northfield	250	Closed				Y				Y	Y	
Optimum	2000	Operating				Y				Y	Y	

Phoenix	430	Operating				Y				Y	Y	
Polmaise	60	Operating								Y	Y	
Rietspruit	2200	Operating		Y						Y	Y	Y
Rondebult	150	Closed								Y	Y	
Secunda: Twistdraai	1800	Operating								Y	Y	
Secunda: Syferfontein	700	Operating	Y									
South Witbank	400	Closed						Y		Y		
Tavistock: No 4 Seam	260	Operating					Y	Y		Y		
Tavistock: No 5 Seam	160	Operating						Y		Y		
Van Dyks Drift - LAC Plant	750	Operating			Y					Y	Y	
Van Dyks Drift - PSS Plant	1800	Operating				Y				Y	Y	
Waterpan	400	Operating								Y	Y	
Witbank Consolidated	590	Operating						Y		Y		
Woestalleen	160	Operating				Y				Y	Y	
Zaid	350	Operating				Y				Y	Y	
Golfview	240	Operating				Y				Y	Y	
Spitzkop	450	Operating				Y				Y	Y	
Strathrae	400	Operating							Y	Y	Y	
Sumo	250	Operating				Y				Y	Y	
Tselentis (Bothasrust)	400	Operating								Y	Y	
Delta Colliery	180	Operating				Y				Y	Y	
Grootegeluk	8200	Operating			Y					Y	Y	Y
Tshikondeni	250	Operating								Y	Y	Y
New Vaal	1200	Operating		Y								
Springlake	400	Operating						Y		Y	Y	
Durban Navigation	500	Operating		Y						Y	Y	Y
Umgala	220	Operating						Y		Y		
Alpha Anthracite - (Ami)	150	Operating				Y				Y	Y	
Heritage	120	Closed				Y				Y	Y	
Hlobane	480	Operating								Y	Y	Y
Zululand Anthracite	250	Operating				Y				Y	Y	

Some settled fines are re-mined and incorporated into the coal supply to PC fired power plants. This was in progress from Dam No 3 at Grootegeluk Mine when the activities of the Exxaro Resources Limited were reviewed (Waldeck and Dixon, 2005). The recovered material was blended with the coal supply for Matimba and this practice was expected to continue with material from Dam No 5. The instigation of drying beds for fine discard to provide material for blending into the power plant was also planned and this was expected to remove the need for further dams to be constructed at this mine.

However, such recovery and use of discarded material appeared not to be the norm for the company and was not reported at the other mines. At Leeuwpan the settled fines would either be sold for brick making or stockpiled and capped. Advanced filter presses were being installed to dewater the slimes so that they could be disposed of with coarse material to avoid future use of settling ponds. Fines slurry is reprocessed and discard material is co-disposed with the power plant's ash at Matla and Arnot and by injection into underground workings at New Clydesdale.

In general Eskom do not view the coal preparation residues stocked around the country as suitable fuel for their conventional PC fired power plants with the high ash, sulphur and moisture contents limiting the proportions that can be included in power plant supplies (Swanepoel, 2008). They did, however view FBC as suitable for discard utilisation though they considered that the levelised generation cost was too high (Van der Riet,2007). At the time unit size and efficiencies were expected to be too low and fuel and sorbent costs too high, even where low grade discard material was used.

The Umbani Power project near Richards Bay in KwaZulu-Natal, conceived in 1997, was for a 270 MW CFBC coal waste fired power plant with an option for an additional 270 MW. The plant has not yet been built mainly because of the difference in the expected cost of power compared with that supplied by Eskom. However, in 2010 the price difference had changed to such an extent that the plant was again being considered (uMhlathuze, 2010).

6.4 Asia and Australasia

6.4.1 Australia

According to the Australian Coal Association (www.australiancoal.com.au/the-australian-coal-industry_coal-preparation.aspx) 80% of all coal mined in Australia is washed including almost all the hard coal exported. Queensland (QLD) and New South Wales (NSW) between them account for around 97% of Australia's coal production. The production statistics from the Australian Coal Association imply that the production in South Australia and West Australia is mainly used as ROM, and Day and Riley (2004) confirm that all West Australian ROM coal is burnt directly in local power stations.

Based on information published by the NSW (www.dpi.nsw.gov.au/minerals/resources/coal/summary-of-nsw-coal-statistics) and QLD governments (Department of Mines and Energy, nd) the total discard rates are shown in Table 36.

Day and Riley (2004) estimated that in 2002, 50 Mt/y washery rejects were produced from 250 Mt of black coal production. Typically 20–25% of ROM coal is rejected from washeries, with coarse waste loose dumped and wet tailings pumped to impoundments.

National Power Australia developed and built the Redbank Power Station, a 150 MW plant in New South Wales. It was designed to use beneficiated, dewatered coal tailings as the primary fuel. In 2001 Redbank was awarded the national Environmental Engineering Excellence Award by the Australian Institute of Engineering. However, in 2010 the then owners, Alinta Energy, assessed the station as effectively worthless due to project financing debt levels and plant performance issues (Adelaide Now, 2010.

Table 36 Discard rates* in New South Wales and Queensland, kt

	2004-05	2005-06	2006-07	2007-08	2008-09	Total
NSW Discard	34,246	36,529	38,990	42,018	43,522	195,305
Underground mines	8,721	9,935	11,039	12,342	11,460	53,497
Open cut mines	25,525	26,594	27,951	29,676	32,062	141,808
QLD Discard	n/a	n/a	n/a	51,306	59,495	110,801
Underground mines	n/a	n/a	n/a	12,912	12,274	25,186
Open cut mines	n/a	n/a	n/a	38,394	47,221	85,615

* these amounts relate to total discard and do not differentiate between material types.

6.4.2 China

In 2006 there were 961 coal preparation plants with a total capacity of 838 Mt/y (Cheng, 2008) and by the end of 2008 there were 1708 coal preparation plants with a total production capacity of 1.38 Gt of coal plus an unknown number of small plants (capacities of less than 90 kt/y) (CCRI, 2010).

According to the China Mining Association (2006) 60.93 Mt of gangue was discharged in 1997. Of this 5.87 Mt was used for power generation and 16.11 Mt for infill and construction and about 4.29 Mt for other purposes. For 1995 they noted that as much as 107 Mt of coal dust were discharged.

Minchener (2004) estimated that in 2000, 100 Mt/y coarse rejects and mining spoil plus 10 Mt/y of tailings were deposited with 1 Gt already accumulated. China Coal Information Institute (2010) reported a total waste from underground coal mining as 350 Mt/y, and an accumulation of more than 5 Gt, occupying more than 16,000 ha. Coal production residues from 1953 to 2009 are shown in Figure 18. These residues are comprised of extraction spoil of 10% to 20% of the coal produced and coal preparation residues of 15% to 20% of the coal washed (*see* Figure 19).

In 2003 189.61 Mt of washed coal was produced and Tsinghua University (2006) assumed that an

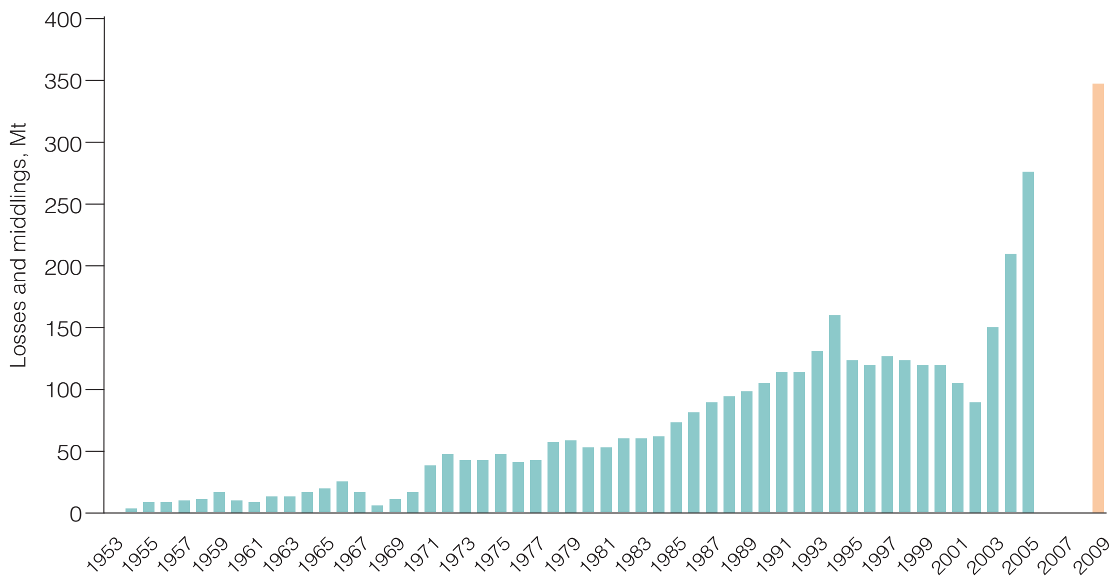

Figure 18 Chinese annual coal production residues (data in green: China Energy Energy Group, 2008; data in orange: China Coal Information Institute, 2010)

amount of slurry equivalent to 1% of the amount of washed coal was produced (about 1.9 Mt). The characteristics of the slurry make it hard to utilise so most of it was being discarded. Three methods of disposal identified were landfill, heaps, and incineration.

China has been utilising at least part of the wastes since the 1970s. CFBC is recognised as a key technology for utilisation of gangue as is briquetting of coal fines to provide low smoke fuels. By 1996 (China Mining Association, 2006):

- 110 gangue-fired pit-head power plants with a capacity of 2 GW had been installed;
- 46 coking plants produced 2.7 Mt/y of coke;
- 47 gangue and coal dust fired cement plants produced 3.50 Mt/y of cement;
- 240 gangue brick yards produced 2 billion bricks per year.

Beijing Huaya Engineering Co (BHEC) (www.chye.com.cn/huayu0/www_English/english.asp) outlined in a company presentation, the history of utilisation of coal preparation residues for power generation in China (*see* Table 37). BHEC have constructed several plants specifically for the

Figure 19 Estimated washery residues in China

Table 37 Utilisation of Chinese coal preparation residues			
Development stage	Fuel types		
	Coal reject	Coal slime	Coal reject + slime
Technology research	1970s	1980s	1990s
Demonstration projects	early 1980s	late 1980s	late 1990s
Gradual promotion	1980s	1990s	post 2000
Unit capacity, MW	3–300	3–135	3–135

utilisation of slurry from washeries. The specification for CWM fuel based on slurry is >25% ash, 55% to 65% solids loading with a stability of 3–5 days.

In Shandong Province at Xinglongzhuang mine BHEC installed what is claimed as the first coal slime power plant in the world. This comprises two 6 MW units, the first of which started operation in 1990 and a 15 MW unit constructed subsequently. Many of the power plants installed to use coal production residues in China are relatively small. More recently (designed in 2005), BHEC provided a rather larger plant 3 x 55 MW to utilise coal slimes and rejects from the Fangshan mine in Shanxi Province and this is described as the largest in China for this fuel.

The IEA CCC Coal Power database identifies 29 CFBC units fired by some form of coal production residue in operation. The total capacity of these is 3925 MW. They came into operation between 2003 and 2008. A further 15 units described as 'planned' or 'under construction' with a capacity of 5 GW are listed. Besides this, one pulverised coal unit of 55 MW also fires this fuel. More than 6 GW of capacity of unknown system type are also listed giving a total potential capacity of 15 GW for utilisation of these fuels.

6.4.3 India

Historically the focus was on washing coking coals, a relatively small part of overall production. Washeries for this purpose were set up in Central Bokaro between 1951 and 1955 (Central Fuel Research Institute, 2006). Coal-fired power plants were designed to accommodate high ash levels (~40%) and the coal supplied to them was not washed.

In 2007-08 the existing coal washing capacity of Coal India Limited (CIL) was 39.4 Mt/y. This was split ~19.7 Mt/y coking coal from 11 washeries commissioned between 1962 and 1997 and ~19.7 Mt non-coking coal from six washeries commissioned between 1958 and 1999 (http://coal.nic.in/welcome.html).

With production at 478.4 Mt in 2007, even at full capacity coal washeries could cope with less than 10% of production. In fact the CIL statistics for the production of washed coal from their coking coal washeries suggest that the throughputs are significantly below full capacity (*see* Table 38).

Indian government action to reduce transport and emission of ash by limiting in many instances the ash content of coals and coal blends to 34% (described in Section 2.2) prompted construction of new washeries. A large part of the new capacity will be provided by third party 'build, own, maintain' (BOM) operations rather than being owned and operated either by coal mining companies or coal using companies which are more usual models. In the period 2000-05, 21 BOM washeries were initiated with a design capacity of 50.15 Mt/y (Singh, 2005). This expansion of coal washing capacity is continuing and CIL anticipates a further 140 Mt of BOM washing capacity between 2010 and 2015 (Ministry of Coal, 2011). Sites for 19 washeries have been identified with an anticipated capacity of 100.6 Mt/y

Table 38 CIL coking coal washery capacities and clean coal production in Mt (Ministry of coal, nd)

Washery	Commissioned	Capacity	1996-97	1997-98	1998-99	1999-2000	2000-01	2001-02	2002-03	2003-04	2004-05	2005-06
Dugda-I	1961	1	0.26	0	0.07	*						
Dugda-II	1969	2	0.48	0.48	0.4	0.48	0.37	0.25	0.24	0.19	0.21	0.55
Bhojudih	1962	1.7	0.86	0.83	0.8	0.83	0.76	0.68	0.66	0.58	0.5	0.67
Patherdih	1964	1.6	0.55	0.34	0.27	0.26	0.23	0.17	0.09	0.08	0.07	0.07
Lodna			0.14	0.1	0.14	0.16	0.11	0.07	0	0	0	0
Sudamdih	1980	1.6	0.39	0.33	0.32	0.36	0.32	0.28	0.25	0.22	0.22	0.27
Barora			0.14	0.14	0.11	0.18	0.1	0.07	0.04	0.01	0	0
Moonidih	1983	1.6	0.49	0.51	0.45	0.51	0.43	0.42	0.41	0.46	0.54	0.49
Mohuda	1989	0.63	0.24	0.25	0.22	0.26	0.25	0.25	0.31	0.3	0.33	0.24
Madhuband	1999	2.5	0	0	0.03	0.13	0.14	0.14	0.16	0.02	*	
Kargali	1958	2.72	1.01	0.79	0.69	0.06	*					
Kathara	1970	3	0.61	0.55	0.55	0.54	0.61	0.65	0.54	0.57	0.58	0.54
Swang	1970	0.75	0.46	0.41	0.43	0.36	0.33	0.35	0.37	0.4	0.38	0.31
Gidi	1970	2.5	0.68	0.62	0.04	*						
Rajrappa	1986	3	1.39	1.02	0.98	0.8	0.81	0.68	0.89	0.99	1.09	0.84
Kedla	1997	2.6	0.01	0.25	0.39	0.34	0.33	0.33	0.38	0.4	0.59	0.61
Nandan	1984	1.2	0.41	0.38	0.35	0.3	0.28	0.26	0.29	0.32	0.34	0.4
Total			8.12	7	6.24	5.57	5.07	4.6	4.63	4.54	4.85	4.98

* converted to a non-coking coal washery

Reject rates from coking coal washeries are reported as 10–15% of raw coal feed, whilst those from non-coking coal washeries are higher at 15–20% of raw coal feed (Kancha, 2006). CIL washeries generated 2.44 Mt of coal washery rejects in 2004-05, with the amount accumulated up to March 2005 estimated as 18.15 Mt (Singh, 2005). The effect on the generation and accumulation of these materials that the increased capacity will lead to is likely to be large.

Washing of fines and slurry is recognised as a key problem due to the very low floatability of Indian coal. By 2006 the Central coking coal washeries produce about 1.6 Mt/y of fines in slurries which the plants were not able to process, largely due the absence of flotation circuits. Therefore this material was discharged to impoundments as tailings, and Central Institute of Mining and Fuel Research (CIMFR, formerly Central Fuel Research Institute, CFRI) were anticipating this rate could rise to 4.75 Mt/y. Treating the –0.5 mm fines from Indian coking coals requires techniques that accommodate their negligible floatability. CIMFR have developed or adapted technologies to address this issue.

Froth flotation technology designed by CIMFR for this application has the following key features:
1 individual design of flotation cell with automatic self-suction of input slurry from conditioner;
2 belt discharge rotary drum vacuum filter in place of rotary disc filter;
3 use of commercially-available synthetic frother instead of pine oil;
4 percolating bed gravity filtration pond for drying of tailings instead of dewatering system;
5 use of low powered indigenously designed emulsifier;
6 completely closed water circuit (zero discharge);
7 no water and air pollution.

The various factors leading to poor floatability in conventional systems have been addressed:
1 sufficient airflow required for floating the hydrophobic materials has been arranged with improved design of diffuser/impeller combination;
2 depending on the nature of aeration and impeller speed the size of air bubbles has been restricted within the desired range;
3 air bubble/coal particle interaction has been increased through positive re-agitation of the pulp through successful design of individual cells, which is not possible in open trough design, especially for inferior grade slurries. Multiple dosing of reagents, as required for optimum yield, are reserved for difficult-to float slurries;
4 transfer of optimum concentrate has been made possible by allowing mixing of pulp at sufficient depth of the cell;
5 provision has been made for final cleaning of the froth with spray of water over the froth-laden surface during removal of concentrate from the cell in order to reduce the final ash content of the concentrate.

Yields of 50–60% clean coal with ash of 12–15% from slurries of 30–35% ash were demonstrated.

Two other technologies applicable to Indian coal fines are Oleo-Flotation and oil agglomeration.

CIMFR developed the integrated Oleo-Flotation process specifically for upgrading and dewatering slurry of –0.5 mm fines. The key steps are:
1 preparation of pulp of 36–40% solid content by thickening of coal slurry of size below 0.5 mm;
2 mixing the pulp with a relatively high proportion of 1 to 1.5% diesel oil or paraffinic oil and 0.05–0.2% of the tat oil of a specific character (obtained from low or medium temperature carbonisation) by weight of dry coal;
3 diluting the oiled pulp with water to 20% solid consistency and floating up the oiled flocs by controlled aeration in a cell;
4 removing the oiled flocs and partially dewatering them on a curved wedge-wire screen;
5 mixing the product with cleaned oversize (x 0.5 mm) in a suitable mixer and dewatering the resultant product in a continuous basket centrifuge.

This enables moisture contents of less than 7% to be achieved without recourse to vacuum filtration or thermal drying. It is effective with fines contents in the mix of up to 30%.

Oil agglomeration was successfully adapted to process Indian coal fines (Central Fuel Research Institute, 2006).

FBC and CFBC were identified as a suitable solution to disposal of washery rejects in an environmentally acceptable manner. Singh (2005) identified opportunities for such plants in each of the three major coalfields where coal preparation residues are likely to be concentrated; North Karanpura (Jharkhand), Talcher (Orissa) and Dipka/Korba (Chattisgarh). By 2006, seven 10 MW were installed at five locations. These were burning coking coal washery rejects with ash contents ranging from 55% to 72% (Kancha, 2006).

6.4.4 Vietnam

Anthracite has been mined in Vietnam for over 160 years with a total of about 350 Mt being extracted in that period. About 103 Mt of this was extracted between 1995 and 2004, during which time production rose from 7 Mt/y to 27 Mt/y. There are five preparation plants with a total processing capacity of 12 Mt/y and the largest of these has a capacity of 6.1 Mt/y. In 2004 around 9 Mt were washed in preparation plants and the remainder was prepared by screening, crushing and blending by the mining companies. In 2005 coal preparation produced 6 Mt of dry rejects and 4.5 Mt of coal slurry. The coastal location of the preparation plants near the China Sea presents significant disposal problems. Three further washeries were planned which would increase this problem (Bach and others, 2006; Bach and Gheewala, 2008, 2010)

Improved cleaning processes have been investigated with a view to mitigating the problem. Introduction of flotation treatments was proposed by Bach and Gheewala (2010). Their investigations found that use of froth flotation would enable about 78% recovery from fines of product of about 10% ash, leaving a slurry reject with over 79% ash which could be discharged to the waste stockpile.

To address the issues of coal preparation residues Truc (2007) identified the following approaches – the construction of new, and modernisation of, existing washeries; the construction of local washeries for recovery of coal from reject piles; use of coal sludge in CWM; and construction of CFBC power plants as options for use of coal preparation residues.

Table 39 Analyses of proposed fuels for Cam Pha power plants.

	Cua Ong Slurry	Cam Pha dust coal No 6 B
Total moisture, %	29.55	8.5
Ash, %	20.1	38
Fixed C, %	45.77	47.53
Volatiles, %	4.58	5.97
C, %	46.21	47.61
H, %	1.72	2.61
N, %	0.57	0.8
S (total), %	0.42	0.65
O, %	1.43	2.03
HHV, kcal/kg	4.15	3.98
LVH, kcal/kg	4.061	3.855

Thao (2004) set out Vinacoal's plan for installation of CFBC power plants, which anticipated installation of about 1 GW of capacity up to 2010 and a further 1.5 GW thereafter. At Cam Pha 6 CFBC boilers have been, or are being, installed. The fuels for these are coal slurry and dry anthracite fines (*see* Table 39).

The plants have been ordered in three phases. Construction of Cam Pha 1 power plant commenced in 2006. It has two 150 MW Foster Wheeler CFBC boilers feeding a single 300 MW reheat turbine. The plant is expected to consume 1 Mt/y fuel. Cam Pha 1 started operating Feb 2010 and the Provisional Acceptance Certificate was dated August 2010. Cam Pha 2 has a similar configuration to Cam Pha 1 and will come online in 2011. In 2009 the Cam Pha 3 project with two 135 MW boilers was approved and will come into operation in 2012.

7 Conclusions

Coal preparation residues have been accumulating for many years. Significant deposits are present where large amounts of coal have been mined, a large proportion has been subjected to preparation and most residual material has been stored.

In Western Europe although the first two criteria are met much of the residual material has been dealt with. There are large deposits of material present in the USA, parts of Eastern Europe, Russia, Australia and South Africa. China and India produce large amounts of coal but the historically low levels of coal preparation mean that stocks are relatively small. The amount of coal preparation residues stored globally is estimated to be large, possibly as much as 58 Gt or, about 800 EJ.

The quality of the residues covers a wide range from material that is better than ROM down to low grade material with very high ash (>80% db) and moisture content. In some cases residues are significantly enriched in sulphur and heavy metals compared to the parent coal.

The size and composition of each deposit of coal preparation residues must be determined to enable assessments of technical and economic feasibility of utilisation to be assessed.

There are several barriers to the recovery and utilisation of coal from these residues:
- economic feasibility which is determined by the value of the coal relative to the costs, including exploratory work to assess residues, reprocessing equipment, licensing and regulatory compliance;
- where urgent action is required there may be insufficient time to implement recovery;
- local opposition to further disruption to the local environment, or general opposition to use of coal, which may be a particular issue if the residues are of low quality;
- technical feasibility which depends on the properties of the residue and the available technology

Opportunities for utilisation of stored residues fall into two broad groups:
- residue recovery and reprocessing to produce coal that meets the specification for standard coal technologies;
- development or adaptation of technologies suited to the properties of the residues.

The technologies range from early stage, speculative (such as recovery of coal from residues using fungi) through those developed to commercial scale (such as the HCGT) to those that are currently in use (such as briquetting and CFBC).

8 References

Adams D M B, Carpenter A M, Couch G R, Fernando R, Henderson C, Moreea-Taha R, Nalbandian H, Niksa S, Nilsson P-A, Rousaki K, Scott D H (2007) *Coal combustion technologies.* London, UK, IEA Clean Coal Centre 2007, Available from: http://www.coalonline.org/site/coalonline/content/browser/81996/Coal-combustion-technology. 286 pp (2007)

Adelaide Now (2010) http://www.adelaidenow.com.au/business/sa-power-station-owner-alinta-energy-to-sell-assets-to-lenders/story-e6frede3-1225927236858 (2010)

Administrative Staff College of India (2010) *Environmental Impact Assessment Guidance Manual for coal washeries*. New Delhi, India, Ministry of Environment & Forests, Government of India, 112 pp (May 2010)

AICE (2004) *A New Way to Recover Large Volumes of Waste Coal*. Available from: http://findarticles.com/p/articles/mi_qa5350/is_200401/ai_n21344484/. USA, American Institute of Chemical Engineers, Chemical Engineering Progress, 1 pp (Jan 2004)

Akers D J, Shirey G A (2005) *Production of New Biomass/Waste-Containing Solid Fuels FINAL REPORT (Phase II)*. DOE Contract No. DE-AC26-99FT40159, Pittsburgh, Pennsylvania, US Department of Energy, 282 pp (Sep 2005)

Akers D J, Shirey G A, Zitro Z, Maney C Q (2001) *Phase I Final Report - Production of new biomass waste-containing solid fuels.* DOE Award No.: DE-AC26-99FT40159, Pittsburgh, Pennsylvania, U.S. Department of Energy, 282 pp (Apr 2001)

Altun N E, Hiçyilmaz C (2001) Evaluation of Çorum Alpagut waste lignite fines. *Physicochemical Problems of Mineral Processing*; 35 (2001); 171-180 (2001)

Amaral Filho J R do, Schneider I A H, Tubino R M C, Brum, I A S de, Miltzarek G, Sampaio C H, Schneider C H (2010) Characterization of a coal tailing deposit for zero waste mine in the Brazilian coal field of Santa Catarina. In: *Proceedings of the 2010 International Mine Water Association symposium : mine water and innovative thinking*, Sydney, Nova Scotia, Canada, pp 639-642 (Jul 2010)

American Bituminous Power Partners LP (2006) Grant Town Power Plant. Presented at: *West Virginia Innovative Energy Summit Oct. 19 2006*, West Virginia, USA, 40 pp (2006)

Astle D R (1993) *Underground disposal and utilisation of colliery waste*. EUR 14872 EN, Luxembourg, Commission of the European Communities, Directorate-General XIII Telecommunications, information Market and Exploitation of Research, 294 pp (1993)

ASTM (2010) *Standard Practice for Minimum Geospatial Data for Representing Coal Spoil and Refuse Features*. ASTM D7629 / D7629M - 10, Philadelphia, Pam USA, American Society for Testing and Materials, 10 pp (2010)

Bach L B V, Gheewala S H (2008) Cleaner production in the coal preparation industry of Vietnam: Necessity and opportunities. *Asian J Energy Environ;* 9 (1 and 2); 65-100 (2008)

Bach L B V, Gheewala S H (2010) Cleaner Production Options at a Coal Preparation Facility in Vietnam. *Journal of Sustainable Energy & Environment*; 1 (2010); 41-46 (2010)

Bach L B V, Gheewala S H, Nguyen T H H (2006) Quality Improvement of Fine Coal in Vietnam by Flotation Method. Presented at: *The 2nd Joint International Conference on "Sustainable Energy and Environment (SEE 2006)",* Bangkok, Thailand, 21-23 Nov 2006, 6 pp (2006)

Battersby M (2011) Maelgwyn Mineral Services, UK, *personal communication*, (March 2011)

Battersby M J G, Brown J V, Imhof R M (2003) The Imhoflot G-cell - An advanced pneumatic flotation technology for the recovery of coal slurry from impoundments. Presented at: *SME Annual Conference*, Cincinnati, USA, February 2003. Available from: www.maelgwyn.com/downloads/Maelgwyn_CoalPonds_Paper.PDF, 6 pp (Feb 2003)

Baychenko A A, Evmenova G (2008) *Utilization of the Kuzbass coal slurry from the outdoor tanks*. Available from: http://masters.donntu.edu.ua/2008/fema/kutsenko/library/stat3.htm, Daktyl, Russia 1 pp (2008)

Bessette R D (2010) *Comments of the Council of Industrial Boiler Owners on EPA Proposed Rule*

Identification of Nonhazardous Secondary Materials That Are Solid Waste 75 FR 31844, EPA-HQ-RCRA-2008-0329, Burke, Virginia, USA, Council of Industrial Boiler Owners, 47 pp (Aug 2010)
Blaschke W S, Gawlik L (2004) Current situation and development prospects of coal preparation in Poland. Presented at: *International Seminar of Coal Preparation Technology, Jiunhua Spa and Resort, Beijing, China, April 19. 2004*. Available from: www.min- pan.kraków.pl/zaklady/zrynek/ zasoby/04_05wb_lg_china.pdf, 33 pp (2004)
Blaschke W S, Gawlik L, Blaschke S A (2006) Coal preparation in Poland. *Gospodarka Surowcami Mineralnymi*; 22 (4); 5-12 (2006)
Blaschke W, Blaschke Z (2005) Preparation of coal slurries deposited in ground settling ponds, *Acta Montanistica Slovaca*; 10 (1); 17-21 (2005)
Bondarenko V I, Pilov P I (2008) Quality changing in technology for brown coal, peat and slimes briquetting. *Gospodarka Surowcami Mineralnymi*; 24 (3/4); 275-282 (2008)
Boyd M (2009) *A shocking crisis*. Mining, Johannesburg, South Africa, Chamber of Mines of South Africa, pp 32-39 (May 2009)
BP (2010) *Statistical Review of World Energy June 2010, chapter 32 Coal*. Available from: www.bp.com/statisticalreview, BP plc, pp 32-35 (2010)
Brecher C, Assmus R C, Brecher J S (1991) *Inductively coupled plasma RF torch*. US Patent 5017751, 7 pp (May 1991)
Brewer D (2011) CoalPro, UK, *personal communication*, (Jan 2011)
BSI (1994) *Glossary of coal preparation terms*. BS3552:1994 / ISO 1213-1:1993, London, UK, BSI, 27 pp (1994)
Budge G, Brough J, Knight J, Woodruff D, McNamara (2000) *Review of the worldwide status of coal preparation technology*. Report No. COAL R199 DTI/Pub URN 00/1205, London, UK, Department of Trade and Industry, 99 pp (2000)
Burnett B W (1993) *Re: Exemption of coal mine waste at the Sunnyside refuse pile, Sunnyside, Utah from Abandoned Mine Reclamation fees*. Letter to Office of Surface Mining Reclamation and Enforcement November 8, 1993, 10 pp (Nov 1993)
Byrnes J G (nd) *Mines of the Donetsk Basin, Ukraine Compilation and working study*. Available from: www.lachlanhunter.deadsetfreestuff.com/JB/Donbass/index.htm, Sydney, Australia, LachlanHunter Services, 1 pp (nd)
Cal Data Ltd (2005) *Capacity building for a national inventory of orphaned/ abandoned mines in Canada, Final report*. Available from: www.abandoned-mines.org, Ottawa, Ontario, Canada, National Orphaned/Abandoned Mines Initiative, 69 pp (Mar 2005)
Carabin P (2011) Pyrogenesis, Canada, *personal communication*, (Feb 2011)
Carabin P, Gagon J-R (2007) Plasma Gasification and Vitrification of Ash – Conversion of Ash into Glass-like Products and Syngas. Presented at: *2007 World of Coal Ash (WOCA)*, May 7-10, 2007, Covington, Kentucky, USA, 11 pp (2007)
Cass B E, Coate D W, Quigley J R (1977) *Method and apparatus for recovering by-product silt fines from a slurry thereof*. United States Patent 4,003,717, 8 pp (Jan 1977)
Castrilli J (2007) *Report on the legislative, regulatory, and policy framework respecting collaboration, liability, and funding measures in relation to orphaned/abandoned, contaminated, and operating mines in Canada.* Canada, The National Orphaned/Abandoned Mines Initiative, 258 pp (Nov 2007)
CCRI (2010) *China's coal preparation*. Available from: www.coalpreparation.cn, Tangshang City, Hebei Province, China, China Coal Research Institute, Coal preparation (Tangshan) branch, 4 pp (Jan 2010)
CDP Plant (2010) McCloskey S130 Screening Plant from CDP Plant Improves Consistency at UK Coal, Available from: www.cdpplant.co.uk/index.php?webpage=news.php&id=118, 1 pp (Jan 2010)
Center for Coal Technology Research (2009) *Indianna coal report 2009*. West Lafayette, Indiana, USA, Purdue University, pp 8-18 - 8-25 (February 2009)
Central Fuel Research Institute (2006) *Past achievements and future prospects of coal R&D*. Dhanbad, India, Central Fuel Research Institute, 285 pp (2006)
Chen S, Khan L, Rostam-Abdi M (2003) *A novel fine coal dewatering process with integrated biomass utilization.* Final technical report, ICCI project no. 02-1/4.1A-2, Illinois, USA, Illinois

Clean Coal Institute, 28 pp (2003)
Cheng W (2008) Clean Coal Technology Development in China. Presented at: *Third Asian Energy Conference - International Conference on China Energy, Kowloon Tong, Hong Kong, 4 Sep 2008*. Available from: www.hkbu.edu.hk/~hkesc/asianenergy/present.htm, 47 pp (Sep 2008)
China Energy Group (2008) *China Energy Databook 7.0 – User Guide and Documentation*. Berkeley, CA, USA, China Energy Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory p 240 (Oct 2008)"
China Coal Information Institute (2010) Development of technical standards and regulations for land reclamation in coal mining areas in China. Presented at: *Asia-Pacific Partnership on Clean Development and Climate, Sixth Coal Mining Task Force Meeting*, Hunter Valley, NSW, Australia, 11-12 Mar 2010, 39 pp (Mar 2010)
China Mining Association (2006) *1.9.3 Improvement of Environmental Protection of Mining*. Available from: www.chinamining.org/Facts/2006-09-22/1158907315d1283.html, Dongcheng District, Beijing, P R China, China Mining Association, 1 pp (September 2006)
Cobb J C, Masters J M, Treworg C G, Helfinstine R J (1979) *Abundance and recovery of sphalerite and fine coal from mine waste in Illinois*. Illinois Minerals Note 71, 15 pp (March 1979)
Committee on Coal Waste Impoundments, Committee on Earth Resources, Board on Earth Sciences and Resources, National Research Council (2002) Coal Waste Impoundments: Risks, Responses, and Alternatives. Washington, DC, USA, National Academy Press, 230 pp (2002)
Couch G (2008) *Coal to liquids*. CCC/132, London, UK, IEA Clean Coal Centre, 114 pp (2008)
Couch G R (1998) *Adding value to coal cleaning wastes.* CCC/04, London, UK, IEA Clean Coal Centre, 51 pp (Apr 1998)
Couch G R (2000) *Opportunities for coal preparation to lower emissions.* CCC/30, London, UK, IEA Clean Coal Centre, 46 pp (Mar 2000)
Couch G R (2002) *Coal upgrading to reduce CO_2 emissions*. CCC/67, London, UK, IEA Clean Coal Centre, 72 pp (Oct 2002)
Crowther M A, Thode Jr H C, Morris S C (1980) *Modules for estimating solid waste from fossil-fuel technologies*. BNL 51474, Washington, DC, USA, The Office of Environmental Assessments, US Department of Energy, pp 4-53 (October 1980)
CSIRO (2002) *CSIRO-Liquatech - Hybrid coal and gas turbine system*. Available from: http://www.csiro.au/proprietaryDocuments/Liquatech.pdf, Australia, CSIRO, Exploration and Mining, Sustainable mining research group, 4pp (2002)
Davcheva-Ilcheva N (1994) Eco-technogenic characteristics of a coal-dressing enterprise. Criteria for ecological assessment. In: *12th International coal preparation congress*, Cracow, Poland, 23-27 May 1991. Poland, JAXA Publishing Ltd, pp 1423-1428 (1994)
Day S J, Riley K W (2004) *Waste streams in black coal mining and coal-fired power generation*. Research report 42, Pullenvale, Queensland, Australia, QCAT Technology Transfer Centre, 41 pp (Jan 2004)
de Koort J G (2000) *Index of South African Coal Preparation Plants*. Available from: http://www.sacoalprep.co.za/papers/South_African_Prep_Plants.zip, Glenvista, Johannesburg, South Africa, South African Coal Processing Society, 1 pp (Jul 2000)
DECC (2009) *Solid Fuels and Derived Gases Statistics: Data Sources and Methodologies*. URN: 10D/790, London, UK, Department of Energy and Climate Change, 17 pp (2009)
Delessard S, Sagnier P H, Palat P E A (1985) *Improving the coal gasification process with a view to the gasification of sludges. (Perfectionnement au procede pour la gazeification du charbon en vue de la gazeification de schlamms)*. EP Patent 0148799 B1, European Patent Office, 6 pp (May 1989)
Department of Minerals and Energy (2001) *National inventory of discard and duff coal*. Summary Report, South Africa, Department of Minerals and Energy, 31 pp (2001)
Department of the Environment (2009) *Reclamation of colliery waste tips: recovery of coal from waste, 1980 Jan 01 - 1987 Dec 31 Department of the Environment: Derelict Land, Registered Files (DL Series)*. File AT42/66, London, UK, National Archives, 240 pp (May 2009)
DHI Water·Environment·Health, Swedish Geotechnical Institute, University of Science and Technology, Kraków (2007) *Classification of mining waste facilities*. No. 07010401/2006/443229/MAR/G4, DG Environment, 207 pp (2007)

Do R T, Leatherman G L (2006) *Plasma pyrolysis, gasification and vitrification of organic material*. USA, United States Patent No. US 6987792 B2, 13 pp (Jan 2006)
Doka G (2009) *Life Cycle Inventory of the disposal of lignite spoil, coal spoil and coal tailings.* Available at http://www.doka.ch/DokaCoalTailings.pdf, Zurich, Switzerland, Swiss Centre for Life Cycle Inventories ecoinvent Centre, 29 pp (November 2009)
Dones R, Bauer C, Röder A (2007) *Kohle. Final report ecoinvent v2.0 No. 6-VI*. Available at: www.ecoinvent.ch, Duebendorf, Switzerland, Paul Scherrer Institut Villigen & Swiss Centre for Life Cycle Inventories, 346 pp (2007)
Drax Group plc (2010) *Annual report and accounts 2009*. Available from: www.draxpower.com/files/page/72/Drax_AR2009.pdf, Selby, North Yorkshire, UK, Drax Group plc,124 pp (February 2010)
Drax Group plc (2011) *Indside Drax. Annual report and accounts 2010*. Available from: http://www.draxpower.com/files/financialreport/138848/Drax_ARA_2010.pdf, Selby, North Yorkshire, UK, Drax Group plc, 120 pp (February 2011)
Ducatman A, ZiemKiewicz P, Quaranta J, Vandivort T, Mack B, VanAken B (2010) *Coal slurry waste underground injection assessment, Final report: Phase II*. Agreement No. G090951, West Virginia , USA,West Virginia Department of Health and Human Resources, Office of Environmental Health Services, 261 pp (July 2010)
Dunn F (2004) *A study of the relationship between various slurry material characteristics and the flow behaviour of co-disposed kimberlite tailings upon deposition*. A dissertation submitted to the Faculty of Engineering and the Built Environment, Johannesburg, South Africa, University of Witwatersrand, 336 pp (2004)
EIA (2006) *Coal Production in the United States*. Available from: http://www.eia.doe.gov/coal/reports.cfm?t=80, Washington, DC, USA Energy Information Administration, 19 pp (October 2006)
Eliezer S, Eliezer Y (2001) *The Fourth State of Matter, An Introduction to Plasma Science, Second Edition.* Bristol, UK, Institute of Physics Publishing, 235 pp (2001)
Energy Daily (2008) *EESTECH And Aryan Clean Coal Technologies Establish Joint Venture*. Available from: www.energy- daily.com/reports/EESTECH_And_Aryan_Clean_Coal Technologies Establish_Joint_Venture_999. html, Sydney, Australia, Energy Daily, 1 pp (October 2008)
EPCAMR (2007) Abandoned Mine Land Impacts and Reclamation via the AML Trust Fund in Pennsylvania. Presented at: *2007 Pennsylvania Statewide Conference on Abandoned Mine Reclamation*, Pennsylvania, USA, 20 – 21 Jul 2007, 18 pp (2007)
Euracoal (2008) *Coal industry across Europe 2008*. Brussels, Belgium, Euracoal, European Association for Coal and Lignite, 76 pp (Aug 2008)
EUREKA (2004) *Enhancement of coal slime by means of complying with the environmental regulations coal upgrading & burning processes*, Project 1570 RESICOAL project outline. Available at: www.eurekanetwork.org/project/-/id/1570, 1 pp (2004)
Evans S (2008) *Understanding the baleen filter (self cleaning micro screen) with reference to the recovery and upgrade of fine coal from the feed to thickeners*. Available at: www.sacoalprep.co.za/Conference2009/28_Baleen%20Filter_Steve%20Evans.pdf, Glenvista, Johannesburg, South Africa, 10 pp (August 2008)
Fecko P, Vales J, Hlavata M, Cablik V, Gondek H (2006) Coal preparation in Czech Republic. *Gospodarka Surocami Mineralnymi;* 22 (4); 13-19 (2006)
Fernando R (2008) *Coal gasification*. CCC/140, London, UK, IEA Clean Coal Centre, 56 pp (Oct 2008)
Fiscor S (2010) Greenfields develops new techniques for recovering coal fines. *Coal Age*; April 2010; 66 - 68 (Apr 2010)
Florea A (2008) Recent developments and the impact of the 2006/21/EC Directive upon the mining industry in Romania. Presented at: *Final meeting – SAFEMANMIN Project,* Brussels, Belgium, 27 Jun 2008. Available from: http://biutec.at/safemanmin/page3.html, Austria, BIUTEC – Biotechnologie und Umwelttechnologie F&E GesmbH, 17 pp (2008)
GEO22 (2009) *Injection Sites by state*. Available from: www.coalslurry.net/data.cfm. West Virginia, USA, West Virginia University, 1pp (2009)

GESI (nd) *The utilization of integrated plasma gasification combined cycle system (IPGCC).* White paper. Available from: www.gesi-solutions.com/6.html, California, USA, Global Environmental Solutions Inc, 6 pp, (nd)
Ghent R (2011) Drax Power, UK, *personal communication*, (Feb 2011)
Ghosh S R (2007) Global coal beneficiation scenario and economics of using washed coal. Presented at: *4th Indo-US coal working group meeting, Ranchi, India, 22-24 Aug 2007*. Available from: http://fossil.energy.gov/international/International_Partners/August_2007_CWG_Meeting.html, Washington, DC, USA, 39pp (November 2007)
Gibbs and Hill Inc (1978) *Coal Preparation for Combustion and Conversion*. EPRI AF-791, Palo Alto, California, USA, EPRI (1978).
Glista J J (2008) *Coal reclamation apparatus and method*. International Publication Number WO 2008/019226 A1, 14 Feb 2008, Geneva, Switzerland, World Intellectual Property Organisation, 35 pp (Feb 2008)
Glynn P J (2008) *A combustion apparatus*. World patent no. WO 2008/070931 A1, 19 June 2008, Geneva, Switzerland, World Intellectual Property Organisation, 22 pp (June 2008)
Glynn P, Wendt M N, Beath A, Mallett C (2005) *Overview of Renewable – Methane Gas to Energy Technology*. CSIRO Exploration and Mining Report. Australia, CSIRO, 21 pp (May 2005)
GOI (1997) *GSR 560(E) 19 September 1997*, India, Government of India, (1997)
GOI (1998) *GSR 378(E), 30 June 1998*, India, Government of India, (1998)
GOI (nd) *Pollution Control Implementation Division – II: Thermal Power Plants*. Available from: www.cpcb.nic.in/profile_pci2.php, India, Central Pollution Control Board of Ministry of Environment & Forests, Government of India, 17 pp (nd)
Góralczyk S (2009) Foresight and the problem of waste from coal mining in Poland. *Mining Review, Monthly Meeting of Mining Engineers and Technicians;* 65 (10); 7-15 (October 2009)
Greb S F, Eble C F, Peters D C, Papp A R (2006) *Coal and the environment*. AGI Environmental Awareness Series, 10, Alexandria, Virginia, USA, American Geological Institute, 68 pp (2006)
Griffen J (1951) Coal preparation in England and Holland. *Transactions AIME*; 190; 183-184 (Feb 1951)
Hall J (2011) Waste2Tricity (UK contact for Alter NRG), UK, *personal communication*, (Feb 2011)
Hand P, Craddock M (2005) *Use of Teetered Bed Separators (TBS) on SA coa*l. Available from: http://www.qva.co.za/downloads/Use%20of%20TBS%20on%20SA%20Coal%20secunda%20paper%20sep%202005%20rev%202.pdf, Australia, QVA Process Technologies (Pty) Ltd, 11 pp (Sep 2005)
Hargreaves Services plc (2010) *Preliminary results for the year ended 31 May 2010*. Available at: http://online.hemscottir.com/ir/hsp/news_xml.jsp?item=493253371636463, UK, RNS news service provided by Hemscott Group Limited. 1 pp (Sep 2010)
Harrison C D, Akers D J (1997) Coal Fines: Resource of the Future. In: *Proceedings Coal Liquefaction & Solid Fuels Contractors Review Conference*, Pittsburgh. 2-3 Sept 1997, Washington DC, USA, US DoE, 6 pp (1997)
Henry C D, Butt B C, Randell J K (1995) Current techniques in the reclamation and treatment of fine coal reject reserves. In: Conference: *20th International technical conference on coal utilization and fuels systems – The year of compliance*, Clearwater, FL (United States), 20-23 Mar 1995. USA, Coal & Slurry Technology Association, pp 583-594 (1995)
Henry C D (2006) Fine coal recovery project Pinnacle Mine Smith Branch impoundment. Presented at: *West Virginia Innovative Energy Summit,* Charleston, West Virginia, USA, Oct 19 2006, Charleston, West Virginia, USA, Marshall University, 39 pp (2006)
Hicyilmaz C (2011) Middle East Technical University, Turkey (retired), *personal communication*, (Feb 2011)
Hinrichs W, Atmaca T, Neumann W, Thormann A (1999) *Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewälther mieralischer Rohstoffe, Teilstudie Steinkohle*. Hannover, Deutscheland, Bundesanstalt für Geowissenschaften und Rohstoffe, Staatliche geologische Dienste in der Bundesrepublik Duetschlkand, 124 pp (1999)
Hlavata-Sikorova M, Vitek M (1990) Survey of bituminous coal waste treatment and utilization in the Ostrava-Karvina Coalfield. (Etude du traitement et de l'utilisation des residus bitumineux de charbon dans le bassin houiller de Ostrava-Karvina). In: *Third Int Symp on the Reclamation,*

Treatment and Utilization of Coal Mining Wastes, Glasgow, UK, 3 Sep 1990, Rotterdam, NL, Balkema publ, pp 365 - 368 (1990)

Honacker R (2005) *Premium fuel production from mining and timber waste using advanced separation and pelletizing technologies. Final report (Phase II)*. DOE Contract No. DE-FC36-02ID14273, Pittsburgh, Pennsylvania, USA, U.S. Department of Energy, 218 pp (Dec 2005)

Hotta A, Kauppinen K, Kettunen A (2010) Towards New Milestones in CFB Boiler Technology – CFB 800 MWe / New 460 MWe Super-Critical Plant with CFB Boiler in Lagisza – First Experience Update. Presented at: *Power-Gen Europe 2010,* Rai, Amsterdam, The Netherlands 8 – 10 Jun 2010, 18 pp (Jun 2010)

Hubbert M K (1981) The world's evolving energy system. *American Journal of Physics*; 49 (11); 1007-1029 (Nov 1981)

Hunosa (nd) *The Pereda power plant*. Available from: www.hunosa.es/en/framework.hps, Spain, Hulleras del Norte, S.A. (HUNOSA), 1 pp (nd)

IEA CCC (2011) *CoalPower database*, London, UK, IEA Clean Coal Centre (2011)

IDNR (2010) *Illinois Mining 2009 Annual Statistical Report*. Available from: http://dnr.state.il.us/mines/public/index.htm, Illinois, USA, Illinois Department of Natural Resources, 24 pp (2010)

IDNR (nd) *Annual Statistical Reports*. Available from: http://dnr.state.il.us/mines/public/index.htm. Illinois, USA, Illinois Department of Natural Resources (nd)

Ikaneng M (2010) Operating and developing coal mines in the Republic of South Africa 2010. Pretoria, RSA, Department of Mineral Resources, 70 pp (2010)

Investgazeta (2002) *Lugansk regional state administration summed up*. Available at: www.investgazeta.net/politika-i-ekonomika/luganskaja-oblgosadministracija-podvela-itogi-132579/, Investgazeta, No. 51, 15 Feb 2002, 1 pp (Feb 2002)

IU.ORG.UA (2011) *Clean - first of all: it is understood in the Luhansk region*. Available from: http://iu.org.ua/page.php?id=1205, IU.ORG.UA, 20 Jan 2011, 1 pp (Jan 2011)

Jelks J W (1987) Method of manufacture of pelletized fuel. United States Patent No. 4,828,573, May 9, 1989

Johnson S A, Chothani C, Breen B P (2008) Waste coal fines reburn for NOx mercury emission reduction. DOE Cooperative Agreement No. DE-FC26-06NT42807 Final report, 24 Mar 2008, 18 pp (Mar 2008)

Jordan G, D'Alessandro M (eds) *Mining, mining waste and related environmental issues: Problems and solutions in central and eastern European candidate countries – Joint Research Centre of the European Commission, Ispra,* EUR 20868 EN, Luxerbourg, Office for Official Publications of the European Communities, 208 pp (2004)

Juniper Consultancy Services (2008) *The Alter NRG / Westinghouse plasma gasification process.* Process Review, Bisley, Gloucestershire, UK, Juniper Consultancy Services Limited, 62 pp (Nov 2008)

Kaminski V, Hammack R W, Harbert W, Ackman T, Sams J, Veloski G (2006) Using airborne electromagnetic surveys to identify potential hazards at coal waste impoundments: Examples from West Virginia. In: *7th International Conference on Acid Rock Drainage (ICARD)*, St. Louis, Missouri, USA, 26-30 Mar 2006. Lexington, Kentucky, USA, American Society of Mining and Reclamation (ASMR), 20 pp (Mar 2006)

Kancha P K (2006) Coal fines recovery. Presented at: *US-India Coal Working Group Meeting, Delhi, India, 4-5 Apr 2006*. Available from: http://fossil.energy.gov/international/International_Partners/April_2006_CWG_Meeting.html, Washington, DC, USA, US DoE (2006)

Kent C, Risch C (2006) *Innovative energy opportunities in West Virginia. Final report*. Available from: http://www.marshall.edu/cber/research/Final%20Report%20-20Innovative%20Energy%20Opportunities%20in%20WV.pdf, Huntington, West Virginia, USA, Center for Business and Economic Research, Marshall University, pp 11-18 (Oct 2006)

Khan L A, Berggren D J, Camp L R (1986) *Coal recovery from mine wastes of the historic longwall mining district of north-central Illinois*. IMN 94, Illinois, USA, Illinois State Geological Survey, 23 pp (1986)

Khodakov G S (2007) Coal–Water Suspensions in Power Engineering. *Thermal Engineering*; 54 (1); pp 36–47 (2007)
Kortechvoi Y, Maystrenko A M, Chernyavszii N, Dunayevskaya (1998) Fuel supply variants for Ukrainian anthracite-using power plants. In: *Ukraine/US. Joint Conference on Ukraine Clean Coal Power Plant Upgrade Opportunities*, Kiev, Ukraine 21-24 April 1998, Washington DC, US DoE, pp 83-84 (1998)
Kray C H, Tedesco M J, Bissani C A, Gianello C, da Silva K J (2008) Tannery and coal mining waste disposal on soil. *R. Bras. Ci. Solo*; 32; 2877-2882 (2008)
Kuzev L V (1998) Utilization of fine sediments from Vratchva 1 tailings pond of CWC 'Bobov dol'. In: *Innovations in mineral and coal processing*. Rotterdam, NL, Balkema b v, pp 871-874 (1998)
Laskowski JS, Luttrell G H, Arnold B J (2007) Coal Flotation. In: *Froth flotation*, Littleton, Colerado, USA, Society for Mining, Metallurgy, and Exploration, Inc. (SME), pp 611-634 (2007)
Lavrichshev O A , Messerle V E , Osadchaya E F , A B Ustimenko (2008) Plasma gasification of coal and petrocoke. In: *35th EPS Conference on Plasma Phys*. Hersonissos, Crete, Greece, 9-13 Jun 2008. ECA Vol.32D, O-2.018 4, pp (2008)
Leonard J W, Lawrence W F (1973) Waste coal reclamation. In: *ACS Division of Fuel Chemistry National Meeting*, Dallas, Spring 1973. USA, American Chemical Society Division of Fuel Chemistry, 18(2), pp 232-238 (1973).
Liquid Waste Technology (nd) *Mini-Dredge Slurps Up Tons of Waste Coal from Slurry Settling Ponds*. Available at: www.mudcat.com/coalfines/mini-dredge-slurps.htm, New Richmond, Wisconsin, USA, Liquid Waste Technology, LLC, 1 pp (nd)
Liquid Waste Technology, LLC (nd) *Coal Particles Utilized with the Help of Mud Cat™*. Available from: www.mudcat.com/coalfines/coalparticles.htm, New Richmond, Wisconsin, USA, 1 pp (nd)
Liu H (2006) Coal pipelines - slurry, coal log and other technologies. Presented at: *Zeus Development Workshop on Lowest-cost coal transport technologies for CLT (coal-to-liquids) and IGCC (integrated gasification combined cycles) projects*, 30 March 2006, Houston, Texas, USA. Houston, Texas, USA, Zeus Development Corporation, 88 pp (Mar 2006)
LRC (1985) *Recovery of coal waste*, Research Memorandum No. 425, Frankfort, Kentucky, Legislative Research Commission, 17 pp (Dec 1985)
Magiera T (2007) Country Report on the Characterisation of Mining Waste (Poland). SAFEMANMIN project, Contract No 044126. Available from: http://biutec.at/safemanmin/page3.html, Austria, BIUTEC – Biotechnologie und Umwelttechnologie F&E GesmbH, 14 pp (Mar 2007)
Mak C, Choung J, Beauchamp R, Kelly D J A, Xu Z (2008) 'Potential of Air Dense Medium Fluidized Bed Separation of Mineral Matter for Mercury Rejection from Alberta Sub-Bituminous Coal. *International Journal of Coal Preparation and Utilization*; 28(2); 115-132 (2008)
Masalehdani M N-N, Potdevin J-L, Cazier F, Courcot D (2008) Emission of toxic gases and condensation minerals from burning coal waste heaps in Northern France: Measurements and analyses. In: *ERSEC Ecological Book Series – 4 Spontaneous Coal Seam Fires: Mitigating a Global Disaster*. Beijing, China, UNESCO, pp 13-45 (2008)
Matveev I B, Serbin S I (2007) Modeling of the coal gasification processes in a hybrid plasma torch. *IEEE Transactions on Plasma Science*; Special Issue - Plasma-Assisted Combustion, 35 (6 pt 1); pp 1639-1647 (Dec 2007)
Maurice C, Fuerstenau, Graeme J. Jameson, Roe-Hoan Yoon (eds) (2007) *Froth flotation: a century of innovation*. Littleton, Colerado, USA, Society for Mining, Metallurgy, and Exploration, Inc. (SME), 897 pp (2007)
Miller B G (2005) *Coal energy systems*. London, UK, Elsevier Academic Press, pp 90-95
Miller B G, Miller S F, Morrison J L, Scaroni A W (1997) Cofiring Coal-Water Slurry Fuel with Pulverized Coal as a NOx Reduction Strategy. In: *The Fourteenth International Pittsburgh Coal Conference*, Taiyuan, Shanxi Province, People's Republic of China, 23-27 Sep 1997. Pittsburgh, Pennsylvania, USA, Pittsburgh Coal Conference, 33 pp (1997).
Minchener A J (2004) *Coal in China*. CCC/87, London, UK, IEA Clean Coal Centre, 59 pp (Jul 2004)
Ministry of Coal (nd) *Related annexures*. Available from: http://coal.nic.in/welcome.html. India, Government of India, Ministry of Coal (nd)

Ministry of Coal (2011) *Annual Report 2009 - 2010*, New Delhi, India, Government of India, Ministry of Coal, pp 146 (2011)
Morris P H, Williams J D (1996) Prediction of mine tailings delta profiles. *Transactions of the Institution of Mining and Metallurgy, Section A - Mining Industry*; 105; A63-A68 (Jan 1996)
MSHA (2009) Engineering design manual: Coal refuse disposal facilities. Second edition. Available from: www.msha.gov/Impoundments/DesignManual/ImpoundmentDesignManual.asp. USA, US Department of Labor, Mine Safety and Health Administration, 868 pp (May 2009)
Negreev OV, Papushin JL (1999) *About the energy use of coal-bearing wastes of Donbass*. Available at: http://masters.donntu.edu.ua/2007/fema/svetlichnaya/library/negreev.htm. Collection of abstracts of the conference of young dressers, Donetsk – 1999, 1 pp (1999)
NETL (2008) *Project Facts: Gilberton coal-to-clean fuels and power co-production project*. Available from: www.netl.doe.gov/technologies/coalpower/cctc/ccpi/bibliography/demonstration/coal-processing/ccpi_gilberton.html, Morgantown, West Virginia, USA, National Energy Technology Laboratory, 2 pp (Oct 2008)
Nida D (2004) *Supplemental Environmental Assessment: Paradise fossil plant disposal of coal wash fines Muhlenberg County*, Kentucky. Chattanooga, TN, Tennessee Valley Authority, 50 pp (2004)
Nunes S (2009) *Coal upgrading*. CCC/156, London, UK, IEA Clean Coal Centre, 45 pp (October 2009)
OAO Severstal (2004) *OAO Severstal, the project "Recycling of coal slurry" resulting in savings of about 25 million rubles.* Available from: http://mfd.ru/News/View/?ID=115492, Russia, OAO Severstal, 1 pp (2004)
Ogarenko I (2010) *Problems of Ukraine's coal sector and greenhouse gas emissions from coal mining and consumption*, Kyiv, Ukraine, National ecological centre of Ukraine, 52pp (Dec 2010)
PADEP (2004) *Coal Ash Beneficial Use in Mine Reclamation and Mine Drainage Remediation in Pennsylvania. 2004b*, Available at: http://www.dep.state.pa.us/dep/deputate/minres/bmr/beneficial_use/Index.htm, Pennsylvania, USA, The Pennsylvania Department of Environmental Protection, 410 pp (2004)
Peatfield D (2003) Coal and coal preparation in South Africa—A 2002 review. *The Journal of the South African Institute of Mining and Metallurgy;* 103(Jul/Aug); 355-372 (2003)
Plasma Waste Recycling (nd) www.plasma-wr.com/process.html
Popov P (2007) *Country Report on the Characterisation of Mining Waste (Germany)*. SAFEMANMIN project, Contract No 044126. Available from: http://biutec.at/safemanmin/page3.html, Austria, BIUTEC – Biotechnologie und Umwelttechnologie F&E GesmbH, 34 pp (2007)
Potter H (2011) Environment Agency, UK, *personal communication*, (Feb 2011)
Proctor C P, Crawford J T (1945) Launder washers. In: *Coal Preparation 1945*, Littleton, Colerado, USA, The American Institute of Mining, Metallurgical, and Petroleum Engineers, Ch11, pp 354-384 (1945)
R E Mourdock & Associates, LLC (2006) *Scoping Study: Potential for Fine Coal Recovery from Indiana's Coal Settling Ponds.* Available from: www.purdue.edu/discoverypark/energy/pdfs/cctr/researchReports/Fines-InterimReport-Dec06.pdf, Indiana, USA, Purdue University, 6pp (Dec 2006)
Rajchel M (1995) *Innovative process for concentration of fines particle coal slurries.* Technical report. DOE/PC/92521—T273, Washington, DC, USA,US DoE, 18 pp (1995)
Rajchel M (1996) *Innovative process for concentration of fines particle coal slurries. Technical report March 1,1996, through May 31,1996*. DOE/PC/92521—T282, Washington, DC, USA,US DoE, 29 pp (1995)
Rapp D M (1991) *Process development for production of coal/sorbent agglomerates, final technical report*. DOE/PC/90176—T64, Washington, DC, USA, US DOE, 34 pp (1991)
Rapp D, Lytle J, Berger R (1995) *Production of a pellet fuel from Illinois coal fines.* US DoE contract DE-FC22-92PC92521, Technical Report December 1, 1994 to February 28, 1995, Washington, DC, USA, US DOE 18 pp (Mar 1996)
Rubiera F (2011) INCAR, CSIC, Spain, *personal communication*, (Feb 2011)
Ruiz A S, Chaves A P (2009) Flotação do carvão contido em um rejeito carbonoso (Froth flotation

of coal tailings). *R. Esc. Minas, Ouro Preto*; 62(3); 315-322 (2009)
Ryu C, Finney K, Sharifi V N, Swithenbank J (2008) Pelletised fuel production from coal tailings and spent mushroom compost - Part I Identiofication of pelletisation parameters, *Fuel Processing Technology*; 89 (3); 269-275 (Mar 2008)
Sadovaya Group SA (2010) *Sadovaya Group S A Prospectus*. Luxembourg, Grand Duchy of Luxemburg, Sadovaya Group S A, 366 pp (Nov 2010)
Schimmoller B K, Jacobsen P S, Hucko R E (1995) Prospects for reclaiming fine coal from slurry ponds. In: *International Technical Conference on Coal Utilization & Fuel Systems. The Year of Compliance*. 20-23 March 1995. Washington, DC, USA, Coal & Slurry Technology Association, pp 547-558 (1995)
Schloss L L (2006) *Power projects using methane from coal mines*. CCC/112, London, UK, IEA Clean Coal Centre, 46 pp (Jan 2006)
Shevkoplyas V N, Litvinenko L M (2000) *Microbiological removal of carbon fuel from coal-waste sludge concentrating plant*. Available from: www.eco-mir.net/show/90/, Ecology Environment, 19 Oct 2000, 1 pp (Oct 2000)
Shiao S Y (1993) *Physical cleaning of waste coal by dissolved CO2 flotation.* Final Technical Report US DoE project DE-FC22-92PC92521, Washington, DC, USA, US DoE, 48 pp (1993)
Shipachev V K, Fedorov V I (1998) State of coal preparation industry in Ukraine. In: In: *Ukraine/US. Joint Conference on Ukraine Clean Coal Power Plant Upgrade Opportunities*, Kiev, Ukraine 21-24 April 1998, Washington DC, US DoE, pp 6-7 (1988)
Shirey G A, Jacques M T (1996) Commercialisation potential of a coal-oil agglomeration technology for recovering high quality coal from fine coal waste streams and impoundments. In:*Thirteenth annual international Pittsburgh Coal Conference proceedings "Coal-energy and the environment"*, Pittsburgh, USA,3-7 Sept 1996. Pittsburgh, Pennsylvania, USA, Pittsburgh Coal Conference, volume 2, p 834 (1996)
Shoch D, Brown S, Delaney M (2003) *An assessment of carbon sequestration potential following mine reclamation on the Grant Town Power Project, Grant Town West Virginia.* Available from: www.edison.com/files/2003_granttown_reclamation_report.pdf, Edison Mission Energy, 16 pp (Feb 2003)
Silva L F O, Izquierdo M, Querol X, Finkelman R B, Oliveira M L S, Wollenschlager M, Towler M, Pérez-López R, Macias F (2010) Leaching of potential hazardous elements of coal cleaning rejects. *Environ Monit Assess*; 175 (1-4); 109-126 (May 2010)
Singh V K (2005) Coal washing & power generation from washery rejects. Presented at: *2nd Indo-US coal working group meeting*, Washington, 17-23 November 2005. Washington, DC, USA, US DoE, 16pp (November 2005)
Smith D M, Rauch H W (1987) An assessment of class V well injection of coal mining waste into underground mines in West Virginia. In*: International Symposium on Class V Injection Well Technology*, 22-24 September 1987, Washington DC. Oklahoma City, Oklahoma, Undeground Injection Practices Council, pp 178-205 (1987)
Solena Group (nd) *Plasma Arc Technology (company presentation)*. Available from: www.mcxeec.com/docs/Solena_Group1.ppt, Washington, DC, USA, Solena Group, 64 pp (nd)
Stefaniak S, Twardowska I (2009) Extraction of coal residues from hard coal mining waste dumps as a chance of minimization of their adverse environmental impact. In: Proceedings of the 2nd International CEMEPE & SECOTOX Conference, Mykonos, June 21-26, 2009 pp 1013-1018
Stone & Webster Management Consultants (1998) *Ukraine Completion of Khmelnitsky 2 and Rovno 4 Nuclear Power Generators Economic Due Diligence.* European Bank of Reconstruction and Development, 79 pp (May 1998)
SUEK (2008) *Corporate Sustainability Report of "Siberian Coal and Energy Company", an Open Joint Stock Company for 2007-2008*, Available from: www.suek.ru/en/page.php?id=304, Russia, SUEK, 71 pp (2008)
Swanepoel E (2008) *Fully explore coal discard use to improve security, urges government.* Available from: www.miningweekly.com/article/Fully-explore-coal-discard-use-to-improve-security-urges-government-2008-06-27,27 June 2008, South Africa, Creamer Media, 1 pp (2008)
Tao D, Yu S, Zhou X, Honaker R Q, Parekh B K (2008) Picobubble Column Flotation of Fine

Coal, *International Journal of Coal Preparation and Utilization*; 28(1); 1-14 (2008)
Taulbee D, Patil D P, Honaker R Q, Parekh B K (2009) Briquetting of Coal Fines and Sawdust Part I: Binder and Briquetting-Parameters Evaluations. *International Journal of Coal Preparation and Utilization*; 29 (1); 1-22 (2009)
TenCate (2009) *Geotube® Containers Offer Innovative Solution for Disposal of Coal Mine Slurry Waste, Alabama, USA*. Available from: www.maccaferri.co.nz/wawcs013192/Case-Studies.html, Commerce, Georgia, USA, Tencate Geosynthetics, 2 pp (2009)
Thambimuthu K (1994) *Developments in coal-liquid mixtures*. IEACR/69, London, UK, IEA Clean Coal Centre, 79 pp (April 1994)
Thao N D (2004) Development strategy and the application of circulating fluidized bed combustion in power generation projects of Vietnam National Coal Corporation (VINACOAL). In: *Electricity Supply Industry in Transition: Issues and Prospect for Asia*, 14-16 January 2004, pp 16-24 to 16-34 (2004)
The Coal Association of Canada (nd) *Coal Production by Type and Province*. Available from: http://www.coal.ca/content/, Calgary, Alberta, Canada, The Coal Association of Canada (nd)
The Department of Mines and Energy (nd) *Coal Industry Review 2008-2009 statistical tables, Table 4 - Production by individual mines (tonnes)*. Available from: www.dme.qld.gov.au/mines/coal_statistics.cfm, City East, QLD, Australia, The Department of Mines and Energy (nd)
The European Parliament and The Council of the European Union (2006) Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC. *Official Journal of the European Union;* L 102; 15-33 (April 2006)
Tinnion B (2011) RecyCoal, UK, *personal communication*, (Feb 2011)
Truc K K (2007) Coal supply outlook in vietnam. In: *APEC Clean Fossil Energy Technical and Policy Seminar - Harmonious and Sustainable Coal Power Generation*, Xi'an, People's Republic of China, 16 Oct 2007, APEC Expert Group on Clean Fossil Energy, pp 582-626 (2007)
Tsinghua University (2006) *Improve the Estimates of Anthropogenic Mercury Emissions in China*, Available at: www.chem.unep.ch/mercury/China%20emission%20inventory%20.pdf, United Nations Environment Programme, 62 pp (October 2006)
uMhlathuze Municipality (2010) *City considers a long term power purchase agreement*. uMhlathuze News; Jul 2010; 8 (Jul 2010)
United Nations Economic Commission for Europe (2000) *Environmental performance review Kazakhstan*. New York and Geneva, United Nations, 118 pp (2000)
United Nations Economic Commission for Europe (2001) *Environmental performance review Romania*. New York and Geneva, United Nations, 225 pp (2001)
United Nations Economic Commission for Europe (2002) *Environmental performance review Albania.* New York and Geneva, United Nations, 182 pp (2002)
US Census Bureau (nd) *Economic Census data*. Available at: http://www.census.gov/econ/
US EPA (2011a) *Materials Characterization Paper In Support of the Advanced Notice of Proposed Rulemaking – Identification of Nonhazardous Materials That Are Solid Waste: Coal Refuse. 3 Feb 2011*, Available at: http://www.epa.gov/wastes/nonhaz/define/pdfs/coal-refuse-final.pdf, USA, US EPA, 15 pp (Feb 2011)
US EPA (2011b) *Identification of Non-Hazardous Secondary Materials That Are Solid Waste. EPA Docket ID No. EPA-HQRCRA-2008-0329* Available from: www.regulations.gov, Washington, DC, USA, US EPA (2011)
van der Haagen (1982) The coal problem in Belgium: matters related to the economy and the environment. *Environmental Geochemistry and Health (Minerals and the Environment)*; 4 (2-3); 62-66 (Sept 1982)
Van der Riet M (2007) Clean coal technologies for power generation - a South African perspective. , In: *NEET Workshop on Energy Technology Collaboration*, South Africa, 20-22 February 2007. Paris, France, IEA, 20 pp (Feb 2007)
Venäläinen I, Psik R (2004) 460 MWe Supercritical cfb boiler design for Łagisza power plan. Presented at: *PowerGEN Europe 2004*, 25-27 May, 2004 Barcelona, Spain, 20 pp (2004)

Wagner N J (2007) The characterization of weathered discard coals and their behaviour during combustion. *Fuel*; 87 (8-9); 1688-1697 (Jul 2008)
Waldeck H G, Dixon R (2005) An independent persons' report on the mining assets of Exxaro Resources Limited. Section 7 Tailings. Available from: www.exxaro.com/pdf/icpr/u/downloads.htm, South Africa, Kumba Resources (2005)
Walker S (1999) *Uncontrolled fires in coal and coal wastes*. CCC/16, London, UK, IEA Clean Coal Centre, 72 pp (Apr 1999)
West Virginia State Treasurer (2010) *§11-13A-3e. Imposition of tax on privilege of extracting and recovering material from refuse, gob piles or other sources of waste coal to produce coal*. Available from: www.wvsto.com/dept/Admin/Tax/Documents/CodeSite_11-13A-3e.pdf, West Virginia, USA, West Virginia State Treasurer, 2 pp (Apr 2010)
Westinghouse Plasma Corporation (2002) Westinghouse plasma coal gasification & vitrification technology. Presented at: *Power Generation Conference,* Hershey, Pennsylvania, USA, 16-17 October 2002, 18 pp (2002)
Wibberley L J (2011) High Efficiency Power Using Micronised Refined Coal in Diesel Engines. Presented at: *The 36th International Technical Conference on Clean Coal & Fuel Systems*, Sheraton Sand Key, Clearwater, Florida, USA, 5-9 Jun 2011. 13 pp (2011)
Wibberley L, Palfreyman D, Scaife P (2008) *Efficient use of coal water fuels*. Technology assessment report 74, Pullenvale, Queensland, Australia, QCAT Technology Transfer Centre, 100 pp (Apr 2008)
Wilhelm D, Johnson H, Simbeck D (2002) *Atmospheric Fluidized-Bed Combustion Guidebook – 2002 Update*, Interim report, December 2002. Palo Alto, California, USA, EPRI, 230 pp (2002)
Wilson I (2011) The Coal Authority, UK. *personal communication* (Feb 2011)
World Mining Services (2010) *AFRI-PAL signs JV agreement and relocates factory*, press release 28 Jan 2010, Douglas, Isle of Man, World Mining Services (Jan 2010).
WPCAMR (2001) *Project gob pile - Final project report*. Available from: www.amrclearinghouse.org/Sub/landreclamation/ProjectGobPile, Greensburg, Pennsylvania, USA, Western Pennsylvania Coalition for Abandoned Mine Reclamation, 63 pp (Sep 2001)
Wu Z (2003) *Understanding fluidised bed combustion*. CCC/76, London, UK, IEA Clean Coal Centre, 42 pp (Oct 2003)
Wu Z (2005) *Fundamentals of pulverised coal combustion*. CCC/95, London, UK, IEA Clean Coal Centre, 36 pp (Mar 2005)
Xstrata (2006) Cerrejón Overview. Xstrata Business Analysts site visit, 29 Nov 2006, Available at: http://www.xstrata.com/assets/pdf/xc_20061129_slides.pdf, Zug, Switzerland, Xstrata, 45 pp (Nov 2006)
Yoon R-H, Luttrell G H (2008) *Advanced dewatering systems development*. Final Report (Phase II). DOE Contract No. DE-AC26-98FT40153, Pittsburgh, Pennsylvania, USA, US Department of Energy, 225 pp (Sep 2005)
Zamansky V (1998) *Synergistic utilization of coal fines and municipal solid waste in coal-fired boilers*. Phase I SBIR Final report, US DoE contract no. DE-FG03-97ER82401, Pittsburgh, Pennsylvania, USA, US Department of Energy, 69 pp (Jun 1998)
Zhang W (2007) *Development od an ultra-fine coal dewatering technology and an integrated flotation-dewatering system for coal preparation plants*. DOE Award Number: DE-FG26-05NT42498, Final report, 1 March 2007, Pittsburgh, Pennsylvania, USA, US.Department of Energy, 11 pp (2007)
ZN,UA (2001) *Arbitrator for investor. Mirror of the Week; 12, 24 Mar 2001* Available from: http://www.zn.ua/newspaper/articles/24002, Ukraine, ZN,UA, 1 pp (Mar 2001)

9 Annex – Estimation of global stock of coal preparation residues

Based on the countries for which information was available regional reject rates are estimated (similar to the approach of Dones and others (2007) and Doka (2009) in coal and coal tailings life cycle analysis studies). In this case an average rate for each region, weighted by the national coal production over the period 1981 to 2008, was determined (Table A1).

Table A1 Estimated overall coal production discard rates

Country	Region	Production washed, %*	Washery reject, %*	Washery reject/Total production, %	Raw production 1981-2011, Mt	Weighted average regional reject rates, %
China	Asia Pacific	18	35	6.3	37,586	9.1
India	Asia Pacific	5	50	2.5	7,977	
Australia	Asia Pacific	70	44	30.8	7,213	
USA	North America	50	38	19.0	25,820	19.5
Canada	North America	67	39	26.1	1,835	
Colombia	S & Central America	5†	28†	1.4	848	1.4
South Africa	Africa	52	38	19.8	5,589	19.8
Germany	Europe & Eurasia	100	45	45.0	9,037	37.5
UK	Europe & Eurasia	85	37	31.5	1,772	
Russia	Europe & Eurasia	65	40	26.0	9,042	
Poland	Europe & Eurasia	100	44	44.0	5,589	
Ukraine	Europe & Eurasia	86	47	40.4	3,457	
World	World					19.1

* from Hinrichs and others, 1999
† from Xstrata, 2006

Table A2 Historical world coal production (Hubbert, 1981)

Year	Total, Mt
up to 1860	7,000
up to 1975	158,000
1860 to 1975	151,000

Historical coal production figures were produced by Hubbert (1981) (Table A2). It is assumed that no coal preparation residues were deposited on the surface prior to 1860. Between 1860 and 1976 it is assumed that the amount of fine residue is the same as the global average coal preparation residue production rate for the period 1976 to 2008. This is considered an overestimate but insufficient data were available to produce an alternative estimate for this period.

Table A3 Global and regional coal production from 1981 to 2009 (BP 2010)

Year	World	North America	S and Central America	Europe and Eurasia	Africa	Asia Pacific
1981	3,831	790	11	1,917	136	976
1982	3,980	807	12	1,973	149	1,038
1983	3,986	759	13	1,964	151	1,098
1984	4,191	875	16	1,938	168	1,192
1985	4,420	868	19	2,040	179	1,314
1986	4,528	871	20	2,090	183	1,362
1987	4,629	901	24	2,098	184	1,421
1988	4,734	938	27	2,095	189	1,484
1989	4,817	966	31	2,044	184	1,590
1990	4,719	1,009	30	1,867	183	1,629
1991	4,539	981	31	1,676	186	1,663
1992	4,500	976	33	1,593	182	1,715
1993	4,382	933	32	1,468	190	1,759
1994	4,470	1,019	34	1,351	204	1,861
1995	4,593	1,021	37	1,300	214	2,019
1996	4,668	1,051	40	1,264	214	2,097
1997	4,703	1,078	45	1,242	227	2,110
1998	4,557	1,100	47	1,178	233	1,998
1999	4,544	1,081	46	1,139	229	2,047
2000	4,607	1,054	54	1,165	231	2,102
2001	4,819	1,105	58	1,192	230	2,233
2002	4,853	1,070	53	1,159	226	2,343
2003	5,189	1,044	62	1,186	243	2,653
2004	5,588	1,085	67	1,185	249	3,000
2005	5,896	1,105	73	1,190	249	3,278
2006	6,189	1,132	80	1,207	249	3,520
2007	6,421	1,122	85	1,220	252	3,742
2008	6,781	1,142	87	1,248	254	4,049

The total coal production values for the various world regions were extracted from BP (2010) (Table A3).

The data sets in Table A3 were extrapolated to fill the data gap from 1976 to 1980 (Table A4).

Combining the values in Table A3 and Table A4 and applying the regional reject rates from Table A1 regional reject totals are determined (Table A5).

Assuming no coal preparation residues deposited on the surface prior to 1860 (an incorrect

Table A4 Global and regional coal production (Mt) from 1976 to 1980 (BP, 2010)

Year	World	North America	S and Central America	Europe and Eurasia	Africa	Asia Pacific
1976	3,178	764	9	1,758	83	645
1977	3,309	776	9	1,789	94	714
1978	3,439	789	10	1,819	104	783
1979	3,570	801	11	1,850	115	852
1980	3,700	814	12	1,880	126	922

Table A5 Estimated overall coal preparation discards from 1976 to 2008

Region	World	North America	S and Central America	Europe and Eurasia	Africa	Asia Pacific
Coal production1976 to 2008, Mt	152,331	31,830	1,218	52,088	6,290	61,210
Regional reject rates, %	–	19.5	1.4	37.5	19.8	9.1
Rejects produced, Mt	32,537	6,198	17	19,524	1,243	5,554

Table A6 Estimated overall coal preparation discards, 1860-1975

Region	World
Coal production 1860 to 1975, Mt	151,000
Regional reject rates, %	19.1
Rejects produced, Mt	28,856

Table A7 Estimated overall coal preparation discards, 1860-2008

Region	World
Rejects produced 1860-1975, Mt	28,856
Rejects produced 1976-2008, Mt	32,537
Total, Mt	61,392

assumption as some coal washing using launderers in France and Belgium is known to have occurred from the early 1840s (Proctor and Crawford, 1945). However, the amounts would have been very small in comparison to more recent activities) an amount for the period 1860 to 1976 is estimated by applying an overall average reject rate to the production from 1860 to 1975 (Table A6).

Total potential coal preparation discards is given in Table A7.

Some material has been recovered and used. In the absence of sufficient data for a global estimate to be constructed it is assumed that this figure is about 5%.

The mass of coal preparation residue deposited is estimated as 58 Gt.

The energy content of coal preparation residues covers a broad range from about 5 to 30 MJ/kg, though the most frequently reported values are in the range 12 to 16 MJ/kg. An average value of 14 MJ/kg is assumed.

The energy in stocked fines is estimated as 817 EJ.

Note: Insufficient data were available to differentiate between the treatment of different coal types (hard versus brown).